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13. ABSTRACT *(Maximum 200 words)*

To assemble key researchers in the field of quasi-optical power combining, along with principal representatives of industry and the government who would have potential applications for this technology. To discuss the prospects for military and commercial applications of quasi-optical power combining. To identify key technical issues remaining to be resolved for system application.

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WORKSHOP ON APPLICATIONS AND RESEARCH STRATEGIES

FOR

QUASI-OPTICAL POWER COMBINING

Dr. James W. Mink

3 July 1997

U.S. ARMY RESEARCH OFFICE

DAAH04-95-1-0633

35008-EL-CF

NORTH CAROLINA STATE UNIVERSITY

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

FINAL REPORT

WORKSHOP ON APPLICATIONS AND RESEARCH STRATEGIES FOR QUASI-OPTICAL POWER COMBINING

WORKSHOP OBJECTIVES

To assemble key researchers in the field of quasi-optical power combining, along with principal representatives of industry and the government who would have potential applications for this technology. To discuss the prospects for military and commercial applications of quasi-optical power combining. To identify key technical issues remaining to be resolved for system application.

DATE AND LOCATION OF WORKSHOP

The workshop was held on December 4, 1995 in Raleigh, North Carolina at the Brownstone Hotel.

WORKSHOP AGENDA

The workshop followed the agenda given below:

0830	Welcome
0845	Meeting Objectives
0900	State of the Art of Quasi-Optical Combining and University Research
1000	Industry Issues for Application of Quasi-Optical Devices, Systems
1100	Military System Issues for Application of Quasi-Optical Techniques
1200	Lunch
1300	Panel Discussion with Industry / Military / University Experts
1400	Panel Deliberations (Open to panel members only)
1530.	Presentation of Panel Findings to Director of the Army Research Office

WORKSHOP PANEL MEMBERS AND ATTENDEES

Panel Members:

L. Brockman	Lockheed Martin	
W. Gelnovatch	Army Research Laboratory	(Panel Chair)
W. Carroway	Army Missile Command	
P. Greiling	Hughes Research Laboratory	
D. Westervelt	Harvard University	
W. Kornegay	MIT/Lincoln Laboratory	
M. Stroscio	ARO	
E. Reedy	Ga. Tech.	

Attendees:

J. Mink	NCSU
M. Steer	NCSU
J. Harvey	ARO
D. Rutledge	Cal. Tech.
Z. Popovic	Univ of Colorado
T. Itoh	UCLA
F. Schwering	CECOM
B. Perlman	USARL
R. York	UC Santa Barbara

CONCLUSION OF WORKSHOP

As indicated by the agenda, the state-of-the-art quasi-optical techniques was presented by university and industrial representatives. This was followed by open discussion. General conclusion of the workshop was that quasi-optical techniques hold promise for the generation of large power levels at millimeter wavelengths. All presentation material is attached.

Much research to date focused upon self-oscillating technique which demonstrated that significant power could be generated in the microwave region of the EM spectrum. A significant result of this workshop was that military and potential industrial systems require amplifying systems. This requirement is a result of advanced signal processing techniques utilized by current systems and the need for low noise.

From the technical point of view, concerning quasi-optical systems, two major issues were determined. First, that with the complexity and close coupling of many active devices, further advancements will require the development of computer aided tools to design such systems. The systems are just to complex and cover a wide spectrum of techniques to be resolved through analytical techniques alone. The second major finding of the workshop was that thermal problems may limit the overall performance of quasi-optical systems. Since, the active devices will be embedded in large arrays and because of electromagnetic considerations, they may not have adequate heat removal. This is an issue that must be addressed and further research is required.

At the request of the sponsor, the panel conclusions are not known to the author since the panel provided its recommendations directly to Dr. Iafrate, Director, Army Research Office and they were not made public.

J. Mink

M. Steer

AN OVERVIEW OF QUASI-OPTICAL POWER COMBINING: WHERE WE ARE AND HOW WE GOT THERE

JAMES W. MINK / M. STEER
NORTH CAROLINA STATE UNIVERSITY

OUTLINE OF PRESENTATION

- RELATIONSHIP TO MICROWAVES / OPTICS
- WHY QUASI-OPTICAL TECHNIQUES
- METHODS OF FEEDBACK
- FAMILIES OF QUASI-OPTICAL APPROACHES
- STATE-OF-THE- ART
- CONCLUSIONS

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WHY QUASI-OPTICAL DEVICES

- TO COMPENSATE FOR THE $1/f^2$ PROBLEM ASSOCIATED WITH ACTIVE DEVICES
- TRANSVERSE DIMENSIONS RANGE FROM 10 TO 100 WAVELENGTHS
- RELAXED LONGITUDINAL BOUNDARY CONDITIONS
- EASILY FABRICATED LENSES AND REFLECTORS
- SUBSTANTIAL TRANSVERSE "REAL-ESTATE"
- MANY ACTIVE ELEMENTS MAY BE UTILIZED

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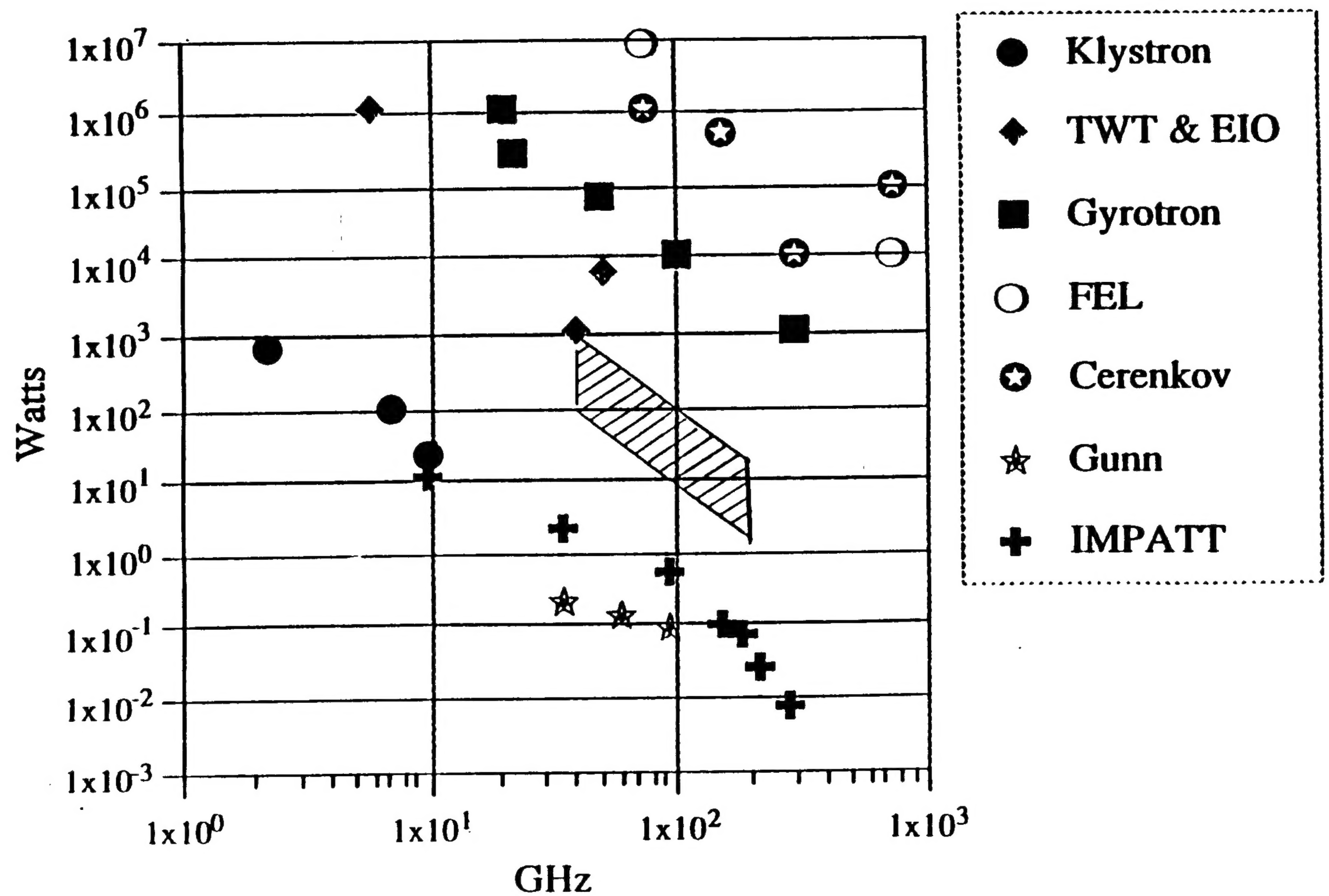
MILLIMETER WAVE SOURCE STATE OF THE ART



SIMILARITY TO THE LASER

- MANY LOW POWER SOURCES ACTING COHERENTLY
- SOURCES MAY BE DISTRIBUTED THROUGH OUT THE VOLUME
- OUTPUT POWER IS IN THE FORM OF A BEAM
- "FABRY-PEROT" RESONATOR
- HIGH SPECTRAL PURITY

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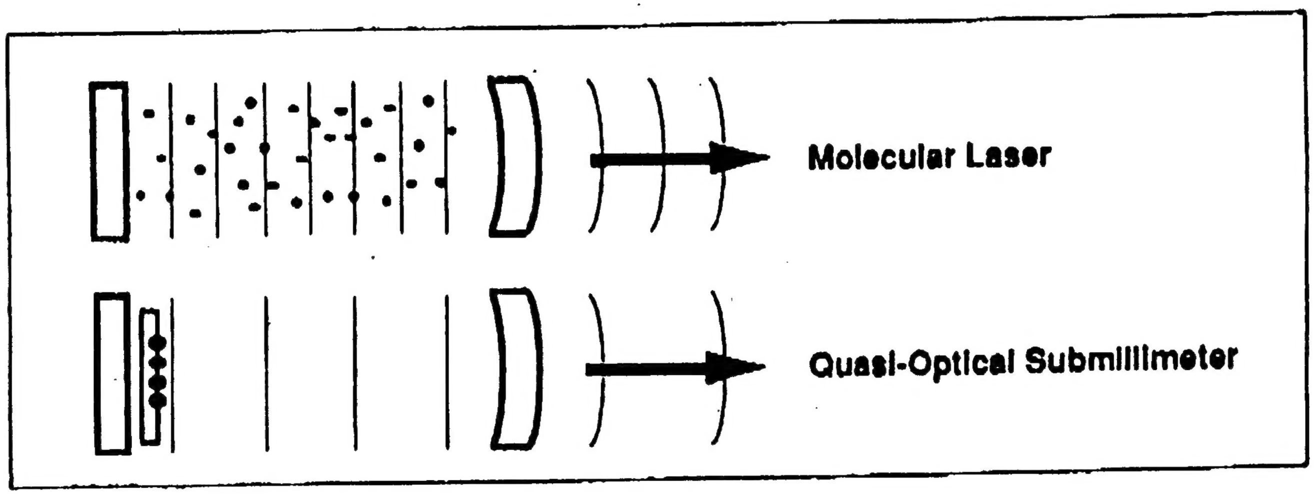
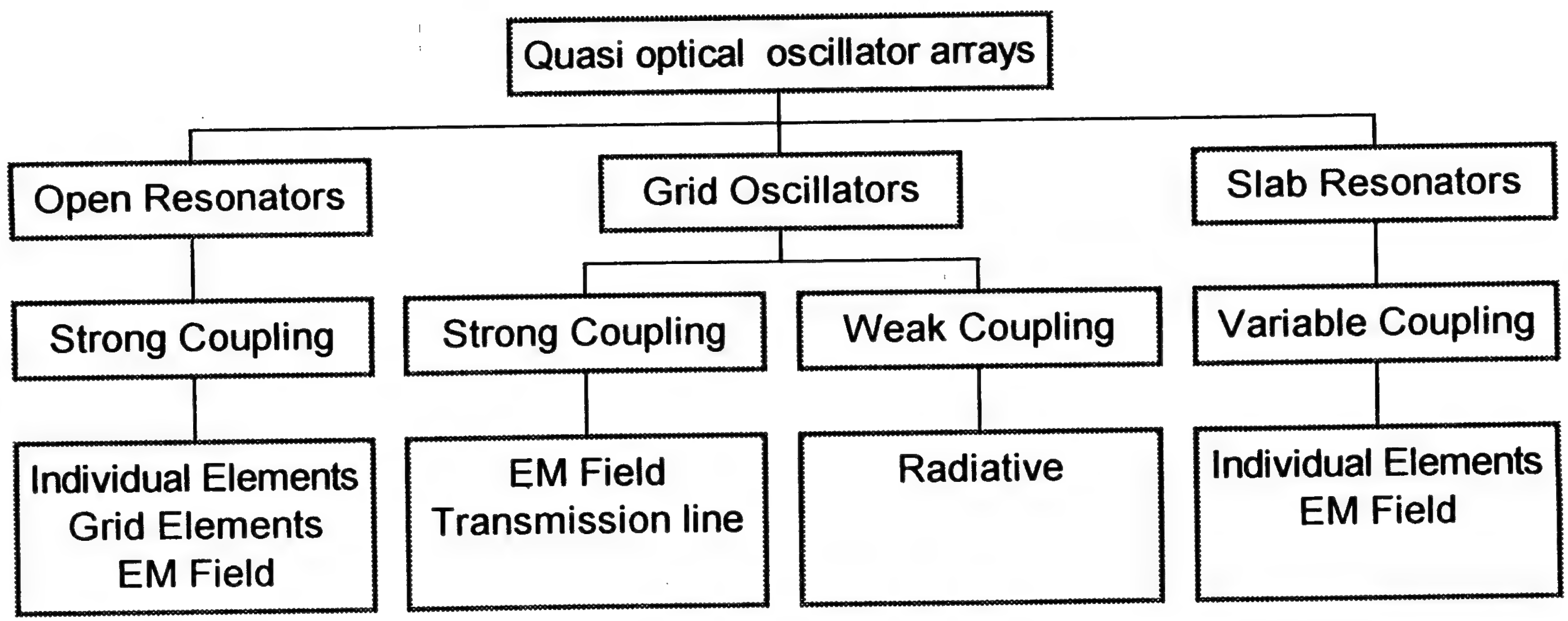
COMPARISON TO LASER



Similarity of Quasi-Optical Technique to Gas Laser

Types of quasi-optical sources



CLASSES OF QUASI-OPTICAL OSCILLATORS: I

- OPEN RESONATOR OSCILLATORS
  - HIGH Q STRUCTURES
  - FEED-BACK VIA ELECTROMAGNETIC WAVE-BEAM MODES

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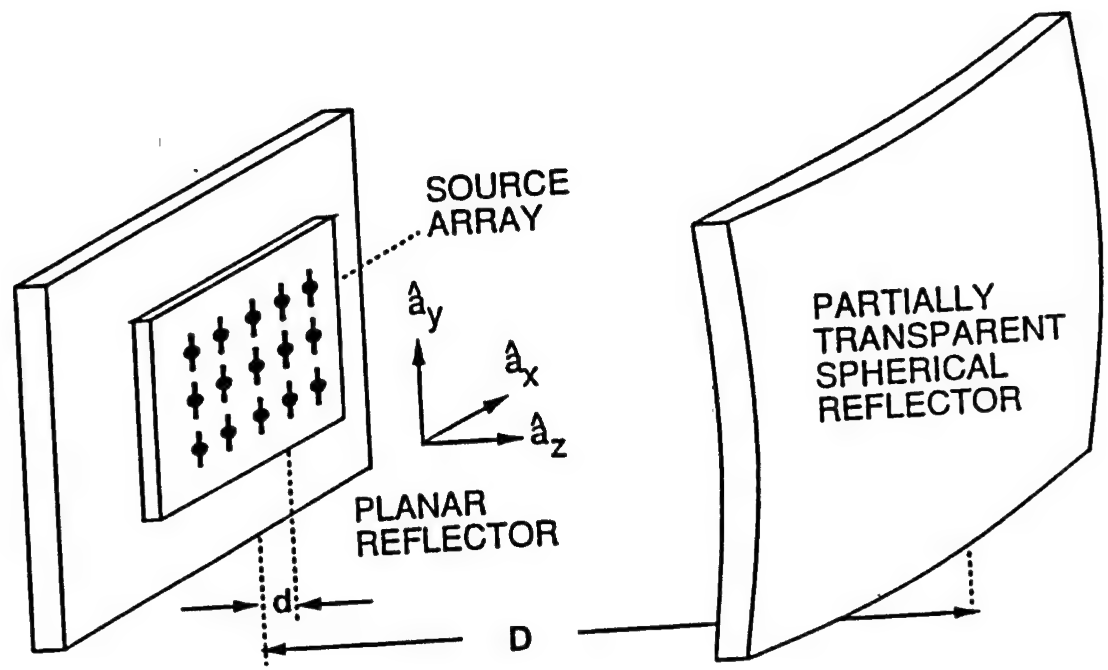
OPEN RESONATOR CONFIGURATION



CLASSES OF QUASI-OPTICAL OSCILLATORS: II

- GRID SYSTEMS
  - LOW Q STRUCTURE
  - PRIMARY FEED-BACK VIA TRANSMISSION LINE COUPLING
  - SECONDARY FEED-BACK VIA ELECTROMAGNETIC WAVE-BEAM MODE
  - INPUT / OUTPUT ISOLATION VIA ORTHOGONAL POLARIZATION

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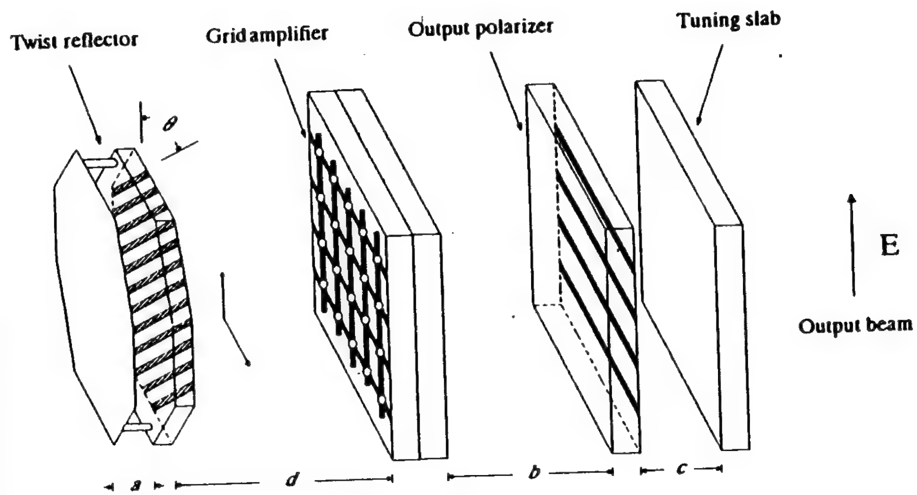
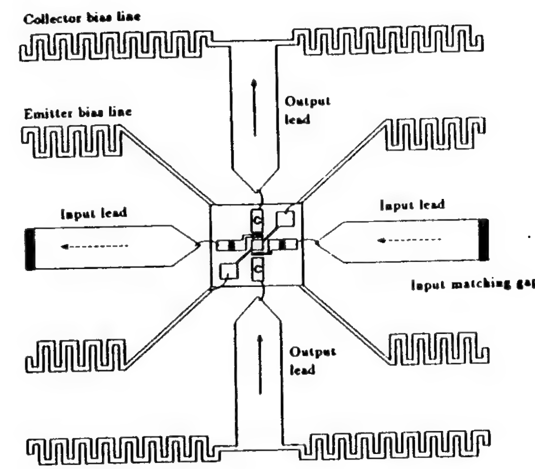
GRID OSCILLATOR CONFIGURATION





CLASSES OF QUASI-OPTICAL OSCILLATORS: III

- SLAB WAVE-BEAM RESONATORS
  - MODERATE TO HIGH Q STRUCTURE
  - FEED-BACK VIA ELECTROMAGNETIC WAVE-BEAM
  - "PLANAR STRUCTURE"
  - TRAVELING WAVE AMPLIFICATION

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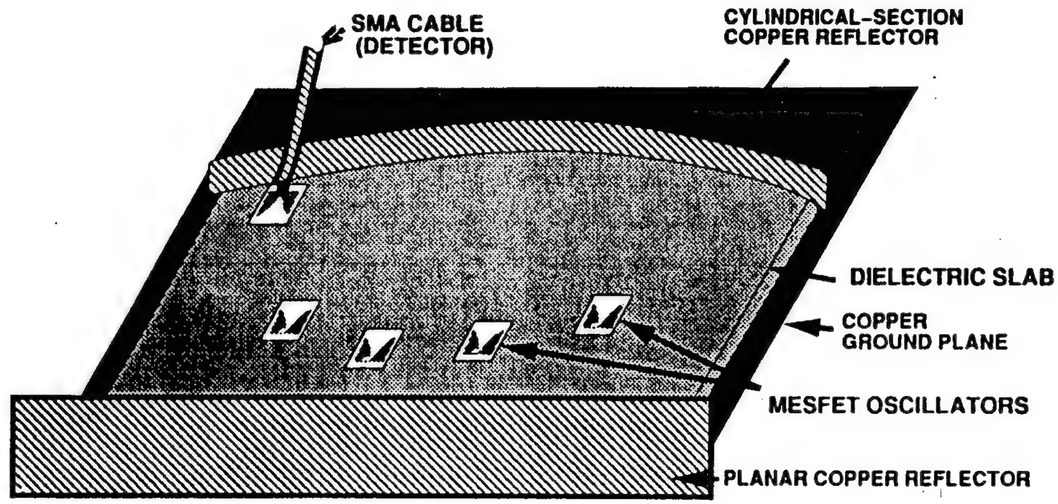
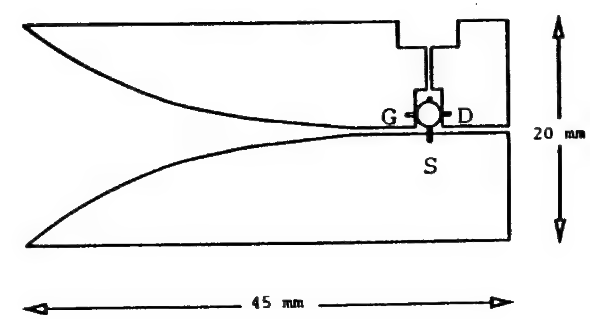
SLAB-RESONATOR CONFIGURATION





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REPORTED QUASI-OPTICAL SOURCES

FREQ (GHz)	ARRAY SIZE	DEVICE TYPE	POWER (mW)	REFERENCE
5.0	10X10	FET	550	Rutledge, et.al.
7.3	3X3	FET	282	Mortazawi, et.al
8.2	4X4	FET	184	York, et.al.
9.8	10X10	FET	10300	Rutledge, et.al.
34.7	6X6	HBT	-	Kim, et.al.
37	4X4	HEMT	-	Wiltse, et.al.
60	2X4	IMPATT	2200	Compton, et.al.

Power combining efficiency ~ 20%

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CONCLUSIONS

- QUASI-OPTICAL OSCILLATORS HAVE BEEN DEMONSTRATED IN EACH CLASS
- EMPHASIS HAS SHIFTED TO THREE TERMINAL ACTIVE ELEMENTS FOR BOTH SOURCES AND AMPLIFIERS
- IMPEDANCE MATCHING FOR MAXIMUM OUTPUT POWER REMAINS A PROBLEM
- CAD TOOLS ARE UNDER DEVELOPMENT AND ARE ESSENTIAL

TWO DIMENSIONAL QUASI-OPTICAL POWER COMBINING FOR MILLIMETER-WAVE COMMUNICATIONS

M. B. Steer

Electronics Research Laboratory
North Carolina State University

mbs@ncsu.edu 919-515-5191

Outline

- Overview of Quasi-Optical Power Combining
- Two-Dimensional Quasioptical Power Combining System
- A Quasi-Optical 2D Power Combining Oscillator
- A Quasi-Optical 2D Power Combining Amplifier
- Future Directions and Needs of Quasioptical Power Combining
  What is required to make active quasi-optics a military/commercial reality

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Contributors

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A. Paolella U.S. Army Research Laboratory
J. Harvey U.S. Army Research Office

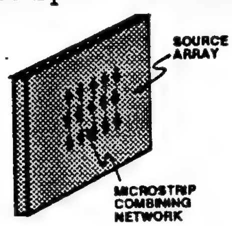
ALSO
D. Rutledge, Z. Popovic, R. York, A. Mortazawi

Applications

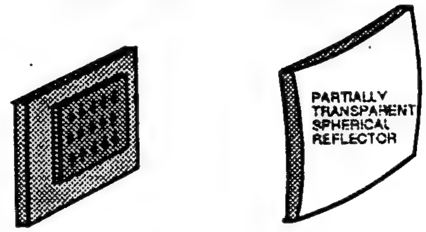
Where Ever You Need More Power than Can be Obtained From A single Solid-State Device

1. Near Vehicle Detection Radar (Collision Avoidance Radar)
2. Millimeter-Wave LAN's (e.g. 60 GHz)
3. Cellular Radio Base Stations
4. Active Missile Seekers
5. Millimeter-Wave Imaging (100+ GHz) Detection of Plastics

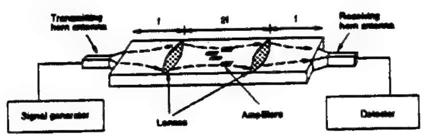
Free Space Combining



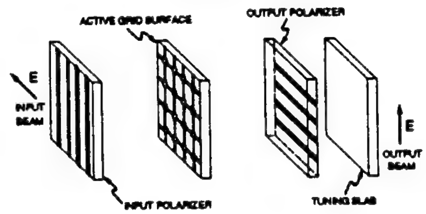
Open Cavity Resonator



2D Power Combiner



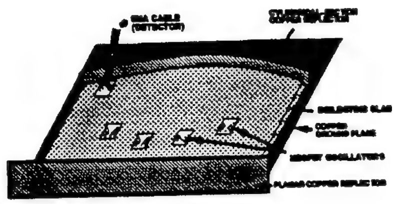
Grid

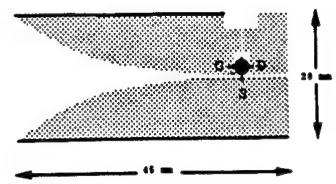


CAE Issues

1. Handling Device-Field Interactions in a Non-Planar Environment.
   — Modeling Paradigm
   — DC-to-Daylight Modeling
2. Handling a Very Large Number of Active Devices in Steady-State Harmonic Balance Analysis.
3. Optimization in Design Requires Steady-State Methods.
4. Handling Distributed High Q Passive Components in Transient Analysis. Turn-on Stability is a major concern.
5. Wholistic Approach required to Achieve High Efficiencies.

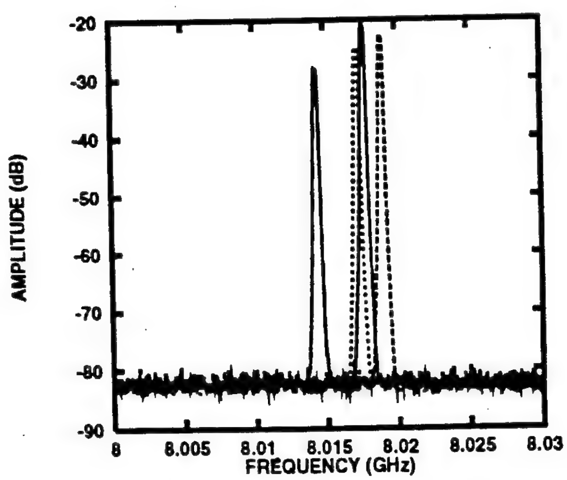
2D Power Combining Oscillator





Spectrum With Four Oscillators

Oscillators Biased One at a Time



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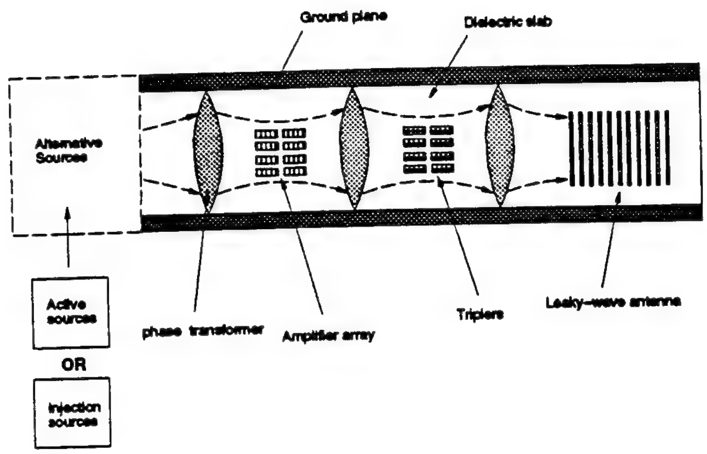
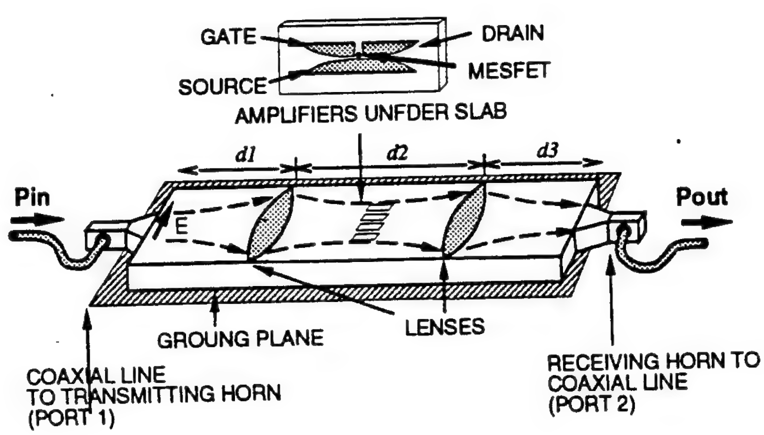
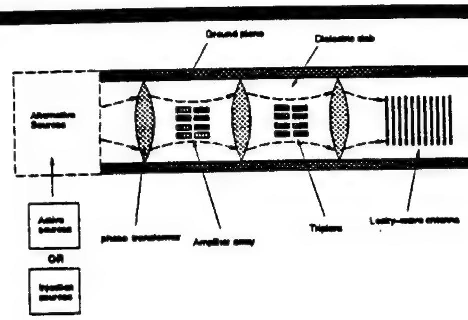
2D Power Combining System



Quasi-Optical Dielectric 2D Amplifier System

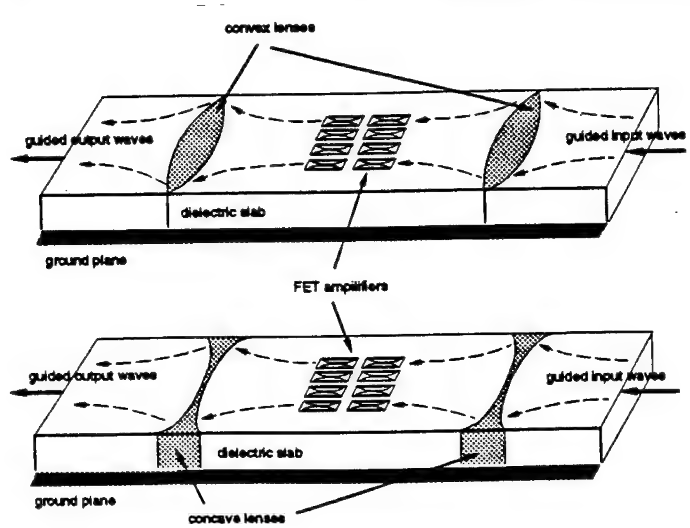


2D Dielctric Quasioptical Power Combining System

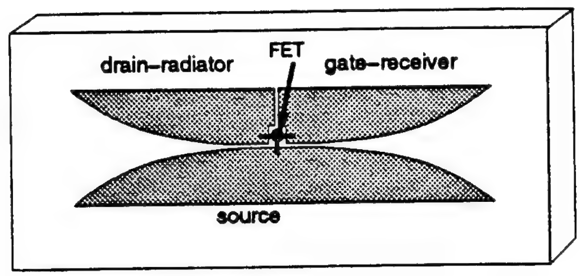


- Resonant Cavity Oscillator Development
- Amplifier/Tripler Array Development
- Lens Development
- Leaky-Wave Antenna Development
- Circuit Model/CAE Tool Development

Amplifier Array in the 2D Dielectric Waveguide

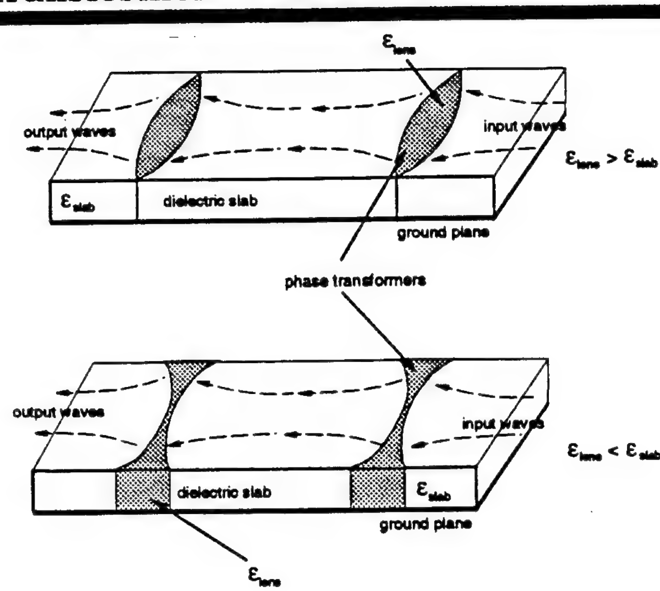


Amplifier with FET

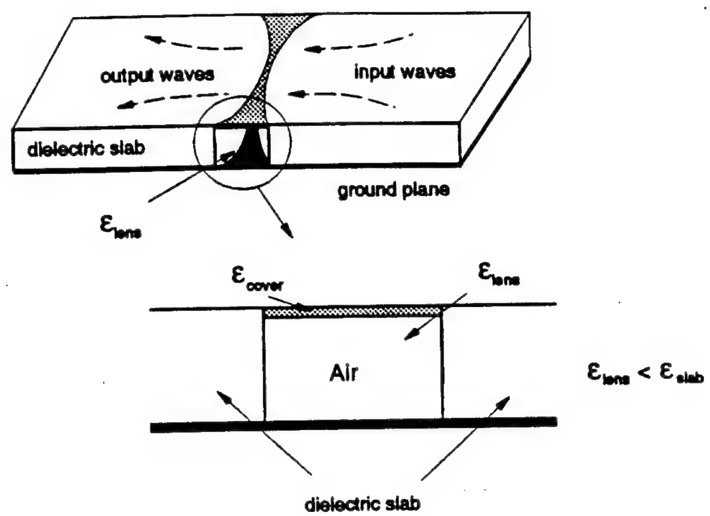


FET ampilifier

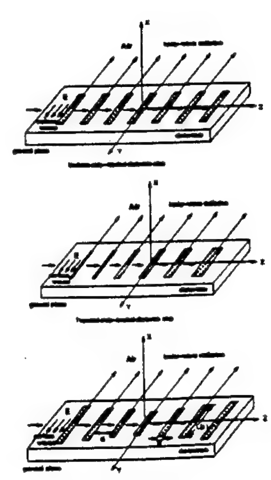
Phase Transformer: Convex and Concave Lenses



Structure of Concave Lens.



2D Dielectric Leaky-Wave Antenna Structures.



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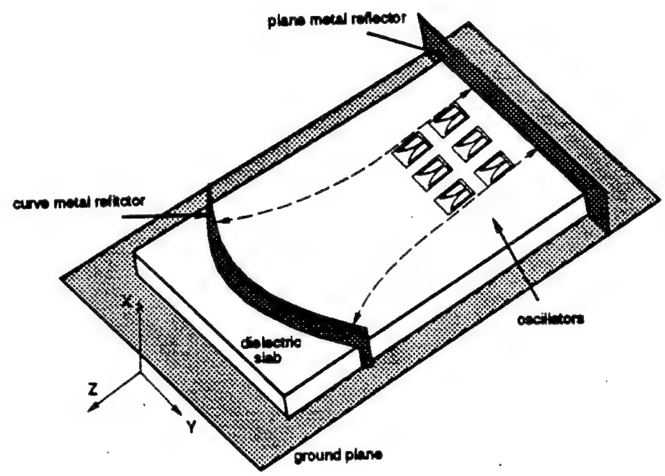
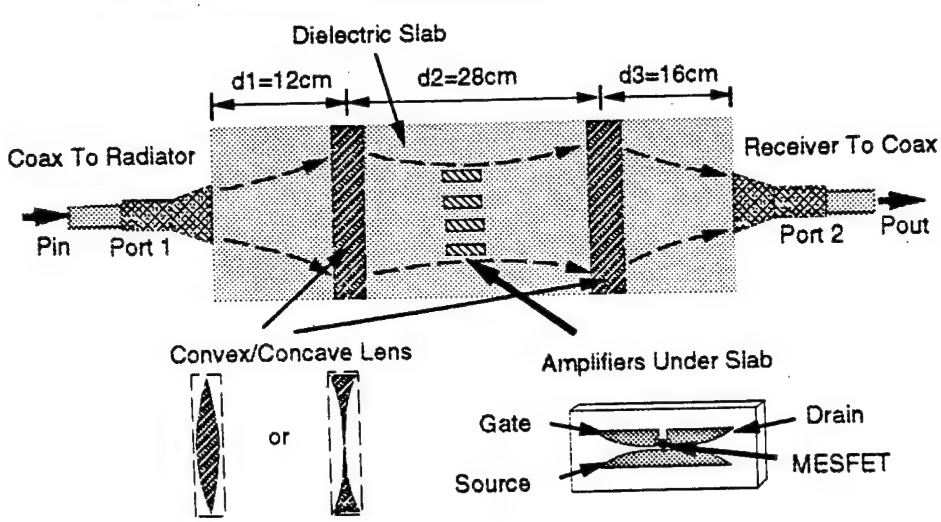
Quasi-Optical 2D Oscillators.



The 2-D System With Convex/Concave Lenses



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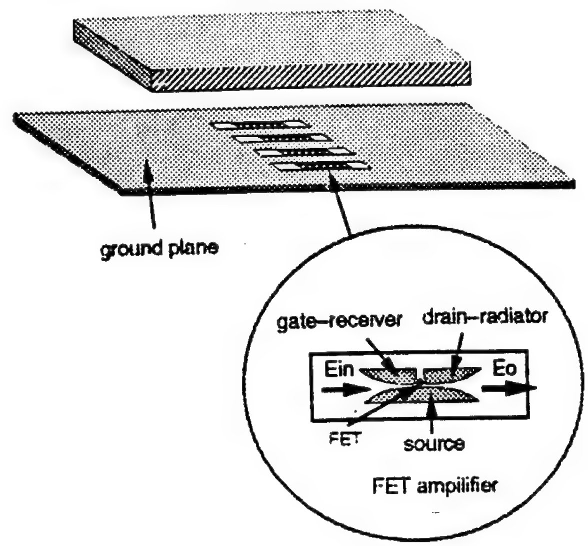
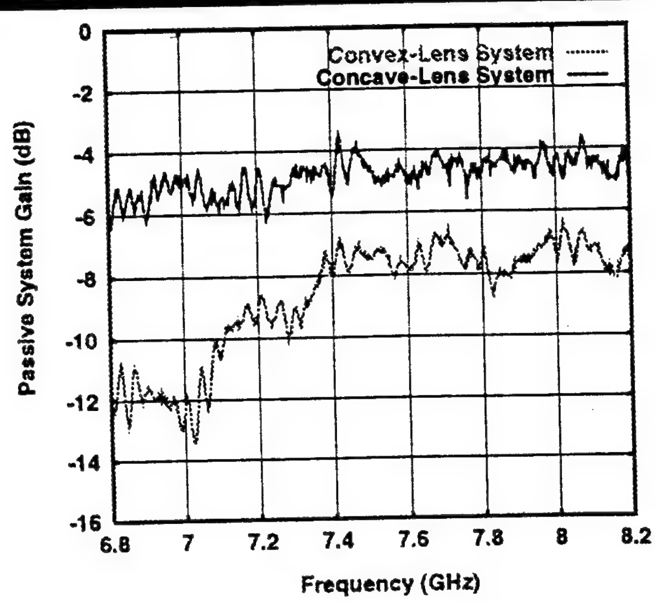
Amplifer Array Underneath The Slab



Passive System Gain (No Amplifiers In The System)



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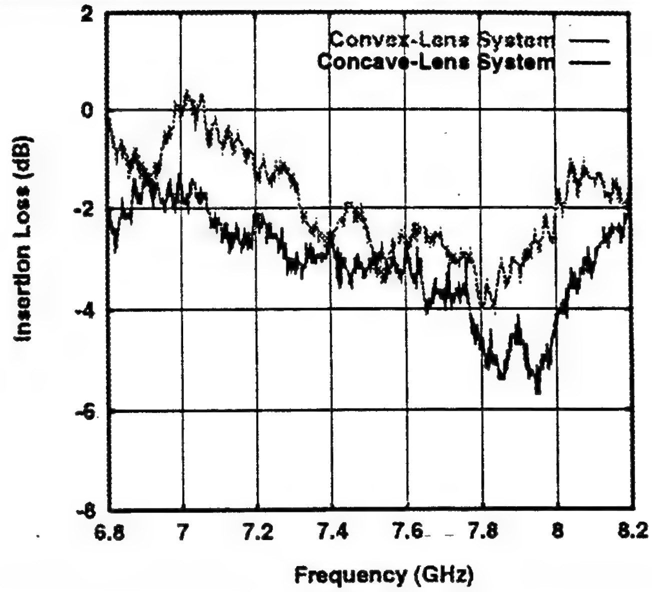
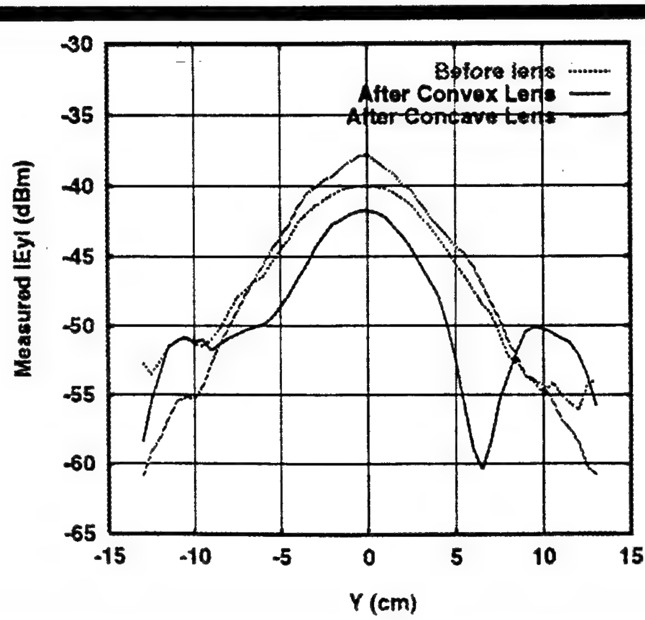
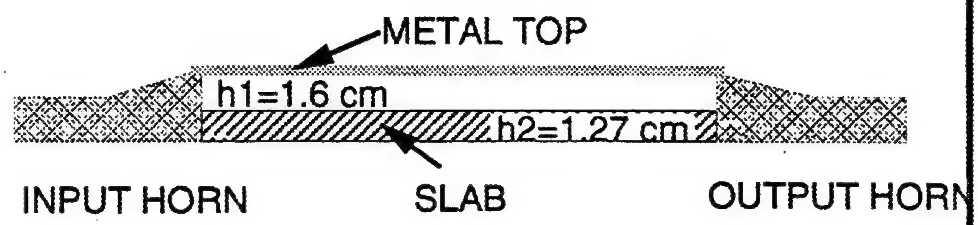
Insertion Loss Of Amplifiers Inside System



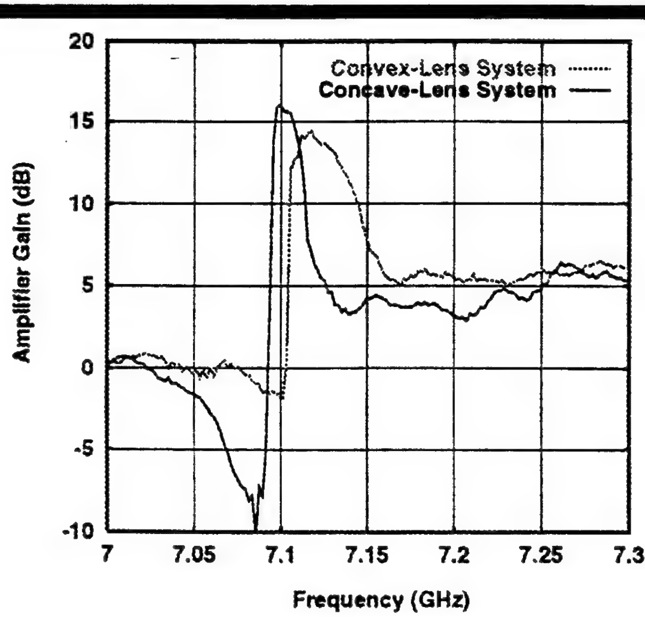
$|Ey|$ Patterns Before and After The Lenses



The 2-D system with A Metallic Top



Amplifier Gains in Convex/Concave-Lens System



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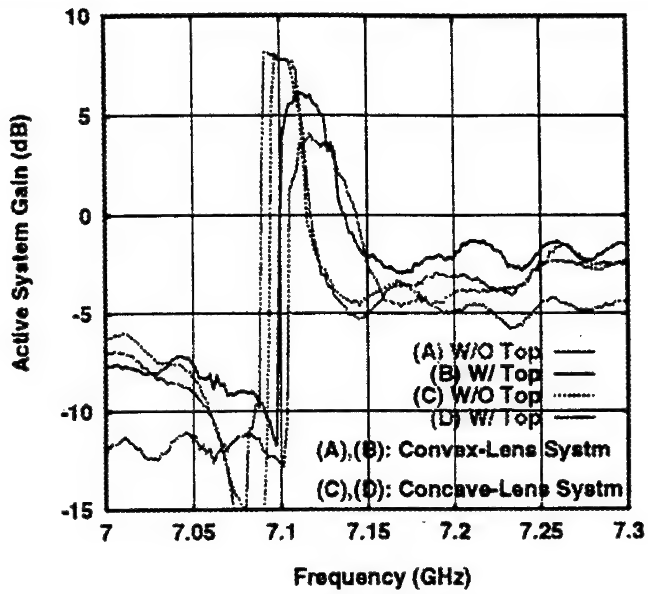
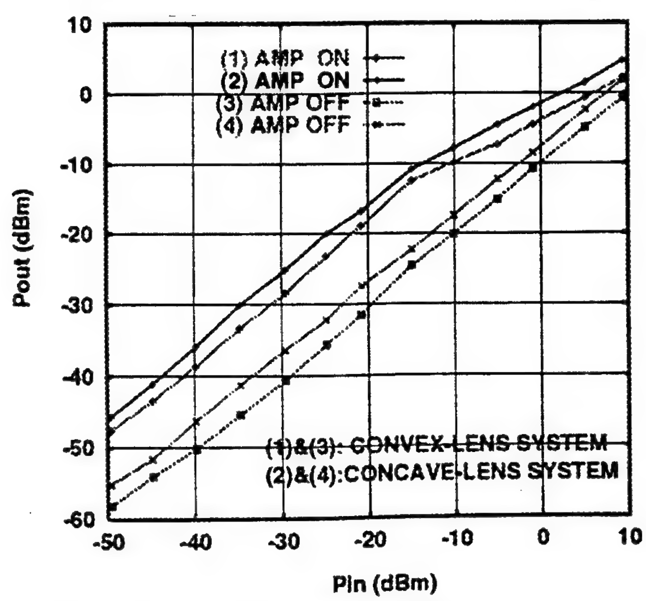
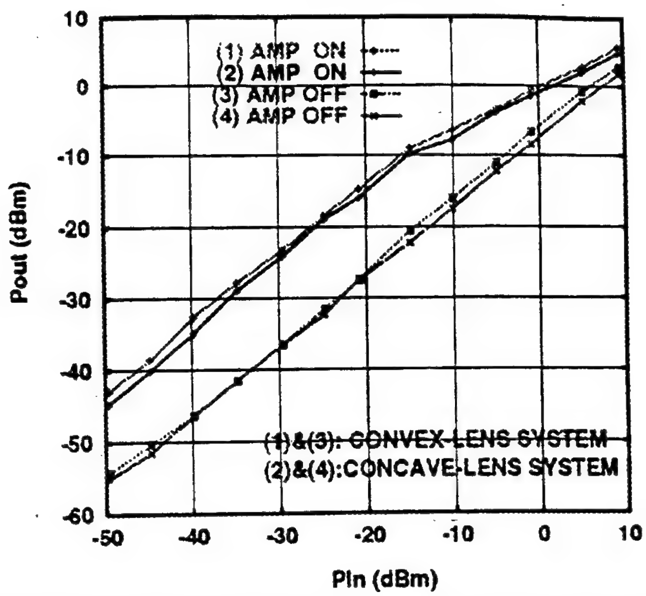
Active System Gains W/ and W/O A Metallic Top



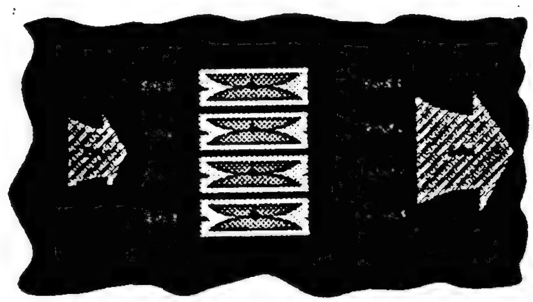
P_{out} V.S. P_{in} W/O A Metallic Top

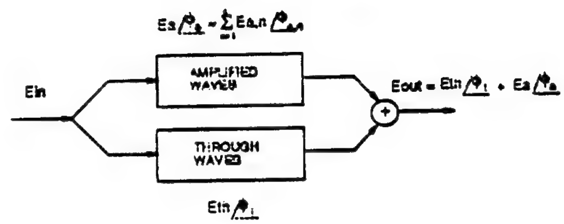


P_{out} V.S. P_{in} W/ A Metallic Top

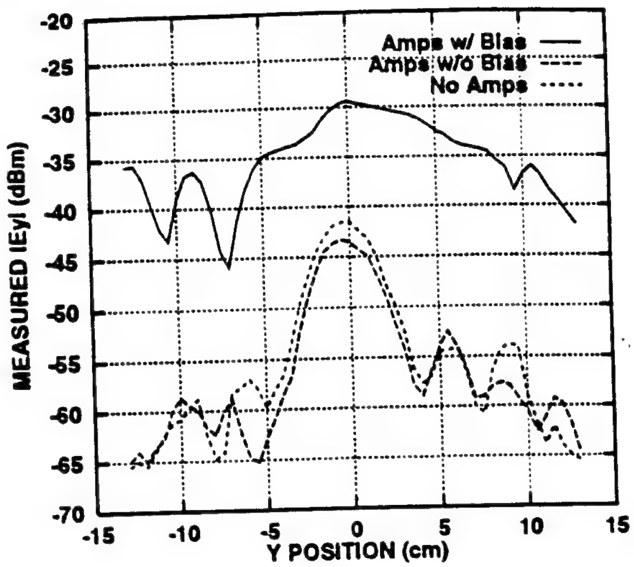


Additive Amplification





Measured $|Ey|$ Near The Receiving Horn



Summary

- A Viable Method of 2D Quasi-Optical Power Combining Has Been Demonstrated
- Amenable to Fabrication Using Photolithographic Techniques and MMIC Technology
- Smaller Size Because of Dielectric
- No Significant Thermal Dissipation Problem
- Resistive Driving Point Impedance Greater Than for Open-Cavity Structures

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... Summary

Requirements:

- Circuit Model/CAE Tool Development
- Development of a calibrated measurement system
- Development of analytic and numerical techniques
- The Lack of Computer Aided Engineering Tools is the Major Impediment to the Development of Quasi-Optical Systems
- Field Analysis Tools

- Transient Analysis (Spice)
- Steady State Analysis (Harmonic Balance)
- In the U.S. addressed by two Small Business Innovative Research Programs
  - MICOM/USARO *Scientific Research Associates*
    working with North Carolina State University
    Custom Quasi-Optical Tools
  - ARPA *Compact Software*
    working with University of Colarado at Boulder & North Carolina State University
    Augmentation of Existing Tools

MAR 15 1996

Acknowledgement

The work is supported by the U.S. Army Research Office DAAL04-95-1-0536, Dr. James Harvey, program manager.

ELECTROMAGNETIC MODELING OF QUASI-OPTICAL POWER COMBINERS

Todd W. Nuteson

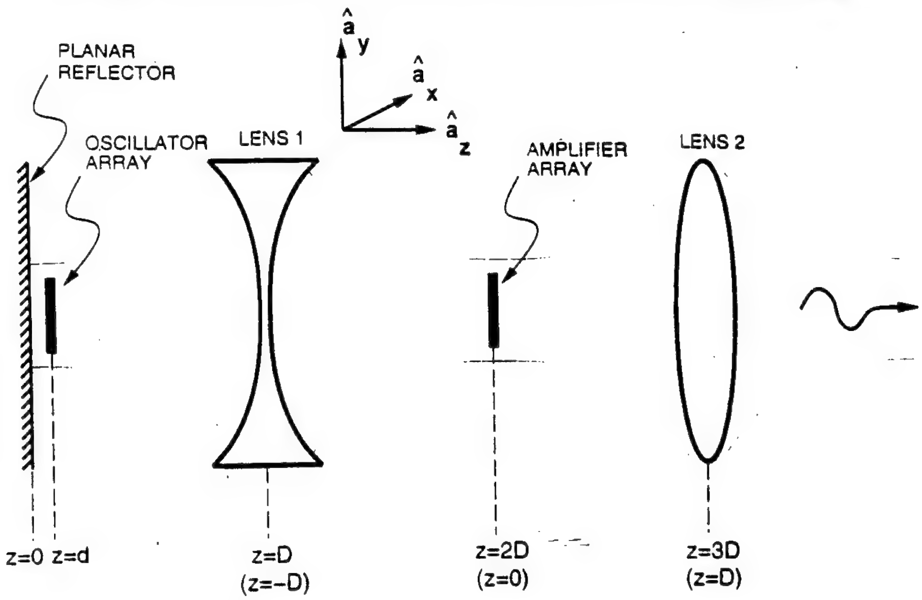
Ph.D. Preliminary Oral Exam
April 1, 1996
10:00 am, 406 Daniels Hall

Electronics Research Laboratory
North Carolina State University

Outline

- Overview of Quasi-Optical Power Combining
- Electromagnetic Modeling
  - Quasi-Optical Green's Functions
  - Method of Moments (MoM)
- Quasi-Optical Systems
  - Open Cavity Resonator
  - Grid Amplifier System
- Summary

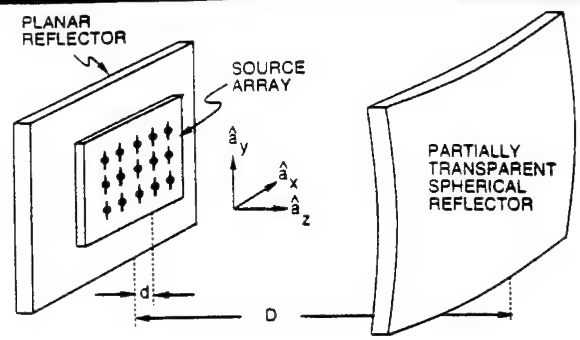
Cascaded Oscillator and Amplifier Power Combiner



CAE Tool Development

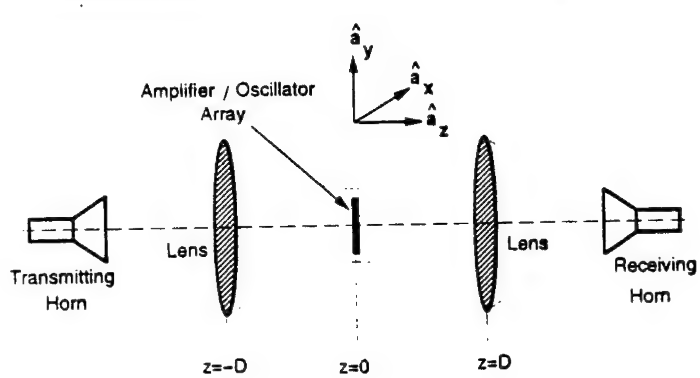
- The Lack of Computer Aided Engineering Tools is the Major Impediment to the Development of Quasi-Optical Systems
- Development of Analytic and Numerical Techniques
  - Field Analysis Tools
  - Transient Analysis (Spice)
  - Steady State Analysis (Harmonic Balance)

Open Cavity Resonator Dyadic Green's Function



$$\overline{\overline{\mathbf{G}}}_E = \overline{\overline{\mathbf{G}}}_{Eh} - \sum_{m=0}^{Nm} \sum_{n=0}^{Nn} \frac{R_{mn}\psi_{mn}}{2\left(1 + R_{mn}\psi_{mn}\right)} \cdot \left[E_{mn}^{-} - E_{mn}^{+}\right]\left[\acute{E}_{mn}^{-} - \acute{E}_{mn}^{+}\right] \overline{\overline{\mathbf{I}}}_t$$

Lens System Dyadic Green's Function



$$\overline{\overline{\mathbf{G}}}_E = \overline{\overline{\mathbf{G}}}_{E0} - \sum_{m=0}^{Nm} \sum_{n=0}^{Nn} \frac{R_{mn}\psi_{mn}}{\left(1 - R_{mn}\psi_{mn}\right)} E_{mn}\acute{E}_{mn} \overline{\overline{\mathbf{I}}}_t$$

Reflection Coefficient

Magnitude:

$$R_{mn} = \Gamma \; \alpha_{d,mn}$$

$\Gamma \;\Rightarrow$ reflection coefficient of lens

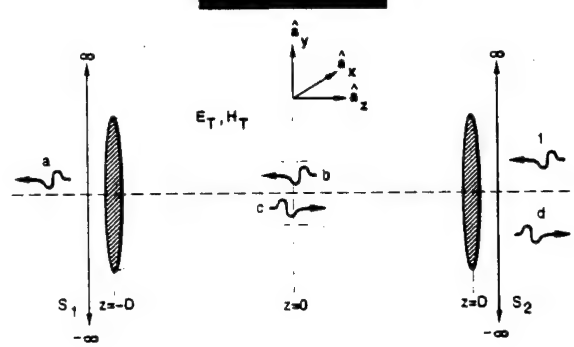
$\alpha_{d,mn} \;\Rightarrow$ diffraction losses

Phase:

$$\psi_{mn} = \frac{E^{+}_{mn}(x,y,D)}{E^{-}_{mn}(x,y,D)}$$

good approximation at $x = y = 0$

Test Fields



$$\mathbf{E}_{T,st} = \begin{cases} a_{st} E^{-}_{st} \,\hat{\mathbf{a}}_x & , \quad z < -D \\ \left(c_{st} E^{+}_{st} + b_{st} E^{-}_{st}\right) \hat{\mathbf{a}}_x & , \quad -D < z < D \\ \left(d_{st} E^{+}_{st} + E^{-}_{st}\right) \hat{\mathbf{a}}_x & , \quad z > D \end{cases}$$

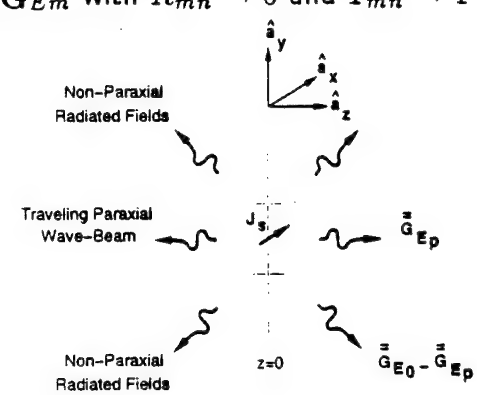
with boundary conditions (R_{mn}, T_{mn}) at each lens, unknown coefficients can be solved

Modal Component

$$\bar{\bar{\mathbf{G}}}_{Em} = -\sum_{mn} \frac{\acute{E}_{mn}}{2(1 - R_{mn}\psi_{mn})} \bar{\bar{\mathbf{I}}}_t \cdot \begin{cases} T_{mn}E^-_{mn} & , \quad z < -D \\ (R_{mn}\psi_{mn}E^+_{mn} + E^-_{mn}) & , \quad -D < z < 0 \\ (E^+_{mn} + R_{mn}\psi_{mn}E^-_{mn}) & , \quad 0 < z < D \\ T_{mn}E^+_{mn} & , \quad z > D \end{cases}$$

Paraxial Component

determined from $\bar{\bar{\mathbf{G}}}_{Em}$ with $R_{mn} \to 0$ and $T_{mn} \to 1$



$$\bar{\bar{\mathbf{G}}}_{Ep} = -\frac{1}{2}\sum_{mn} \acute{E}_{mn} \bar{\bar{\mathbf{I}}}_T \begin{cases} E^-_{mn} & , \quad z < 0 \\ E^+_{mn} & , \quad z > 0 \end{cases}$$

Electric Field Integral Equation & MoM

Total Tangential Electric Field on Conductor Surface is Zero:

$$-\mathbf{E}_t^{scat}(x,y) = \mathbf{E}_t^{inc}(x,y)$$

Scattered Electric Field Relationship to Dyadic Green's Function:

$$\mathbf{E}_t^{scat}(x,y) = \int_{y'}\int_{x'} \overline{\overline{\mathbf{G}}}_E \cdot \mathbf{J}_S(x',y')\,dx'dy'$$

Current Density Expanded in a Set of N Basis Functions:

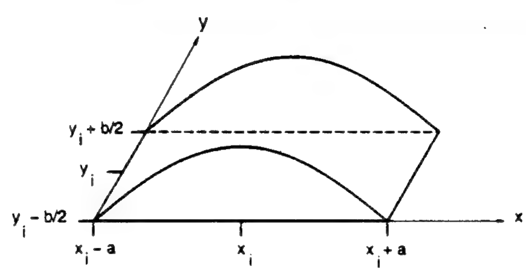
$$\mathbf{J}_S(x',y') = \sum_{i=1}^{N} I_i \mathbf{W}_i(x',y')$$

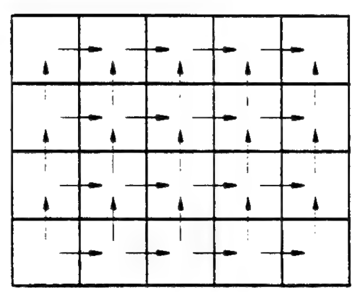
Expansion and Testing (Galerkin Method) Yield Matrix Equation:

$$[\mathbf{Z}][\mathbf{I}] = [\mathbf{V}]$$

Solve for Unknown Currents I_i

Sub-Domain Sinusoidal Basis Functions





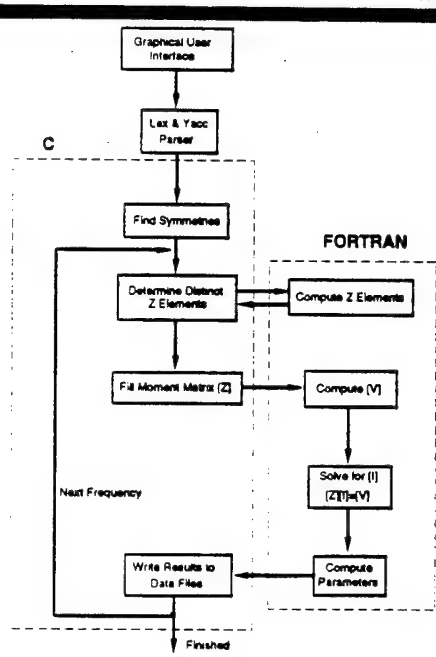
$$W_i^x(x) = \begin{cases} \dfrac{\sin[k_0(a-|x-x_i|)]}{b\sin(k_0 a)}, & |x-x_i| \le a \\ & |y-y_i| \le b/2 \\ 0, & \text{otherwise} \end{cases}$$

Excitation Vector Elements

$$V_j = \int_y \int_x \mathbf{W}_j\,(x,y) \cdot \mathbf{E}_t^{inc}\,(x,y)\; dx\, dy$$

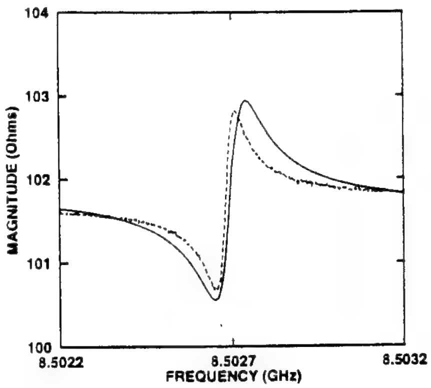
- Incident Field Produced From:
  - Coaxial Current Probe
  - Delta-Gap Voltage Generator
  - Incident Plane-Wave
  - Incident Gaussian Beam-Mode

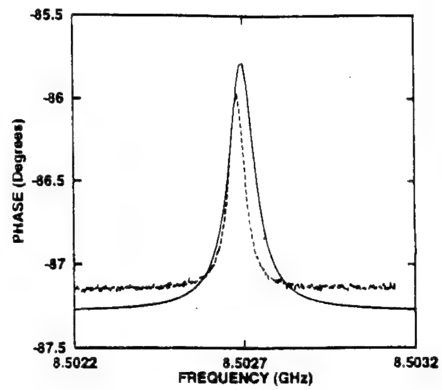
Method of Moments Flowchart



Driving Point Impedance of the Inverted L Antenna

$TEM_{0,0,35}$ mode



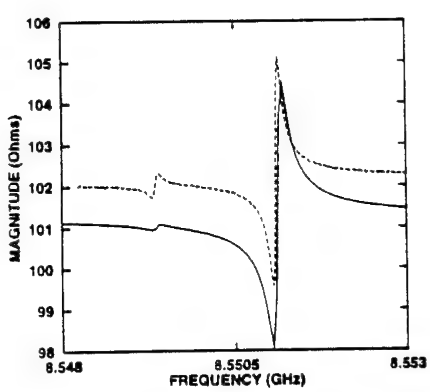


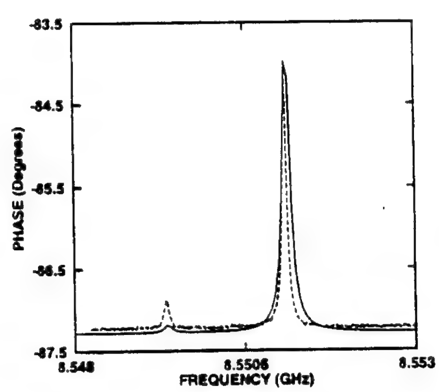
solid line: MoM simulation

dashed line: measurement

Driving Point Impedance of the Inverted L Antenna

$TEM_{0,1,35}$ and $TEM_{1,0,35}$ modes





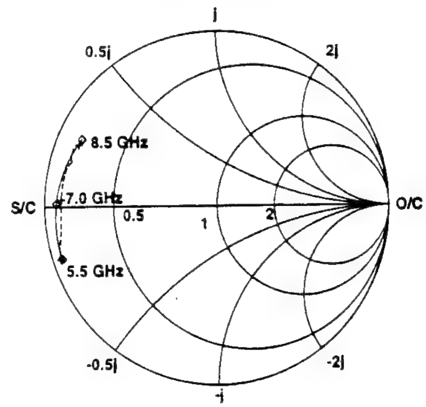
solid line: MoM simulation

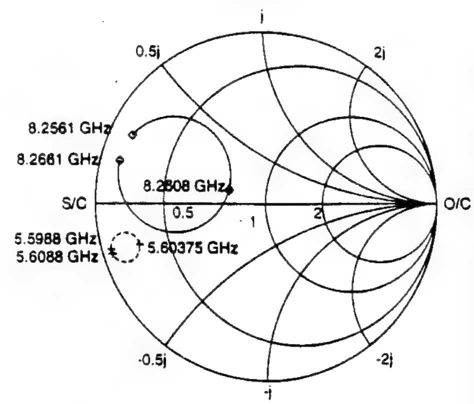
dashed line: measurement

Driving Point Impedance of the Patch Antenna

half-space

cavity
$D = 62.05cm$



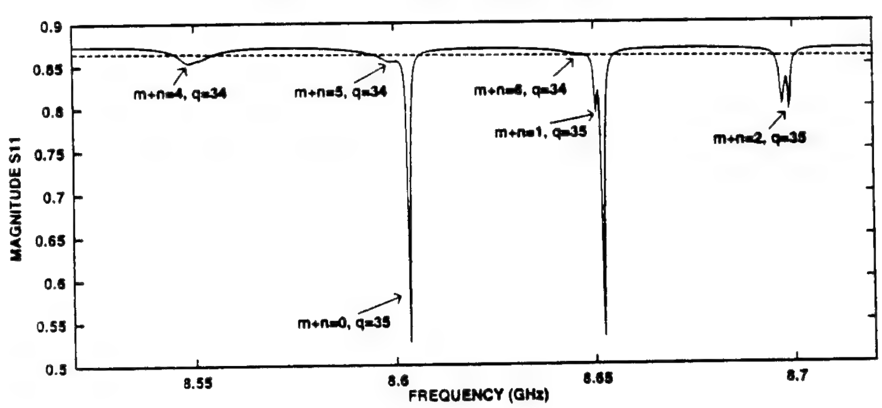


solid line: MoM simulation
dashed line: measurement

solid line: $TEM_{0,0,34}$ mode
dashed line: $TEM_{0,0,23}$ mode

Cavity Field Effects of the Patch Antenna

cavity resonant mode frequencies $f_{m,n,q}$



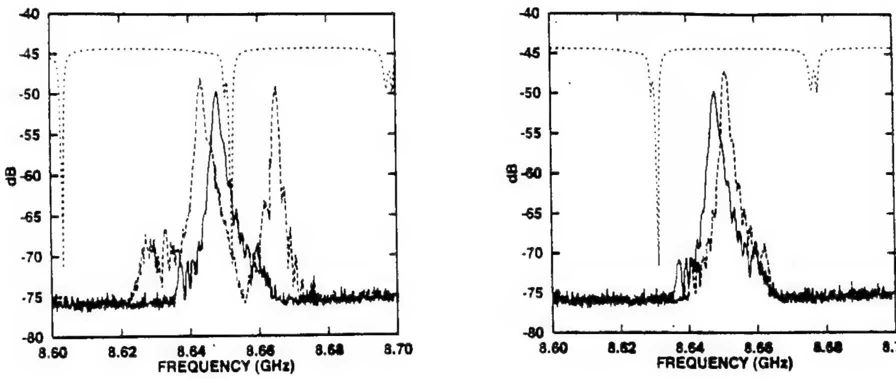
MoM simulation

solid line: antenna in cavity

dashed line: antenna in half-space

Cavity Field Effects of an IMPATT Diode Oscillator

$D = 61.25cm$ $D = 61.4cm$



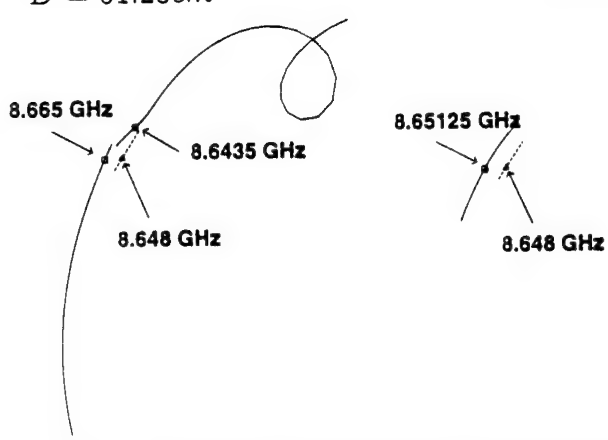
solid line: oscillator in half-space dashed line: oscillator in cavity

dotted line: MoM simulated scaled reflection coefficient magnitude

Driving Point Impedance on Expanded Smith Chart

markers show oscillation frequencies

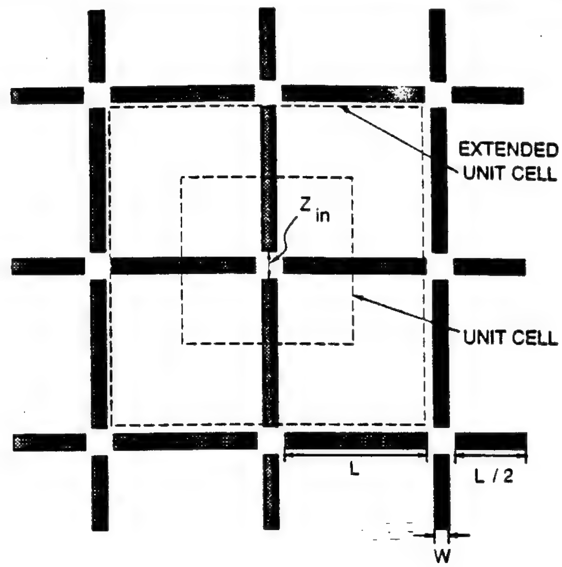
$D = 61.25cm$ $D = 61.4cm$



MoM simulation from 8.63825 GHz to 8.67 GHz

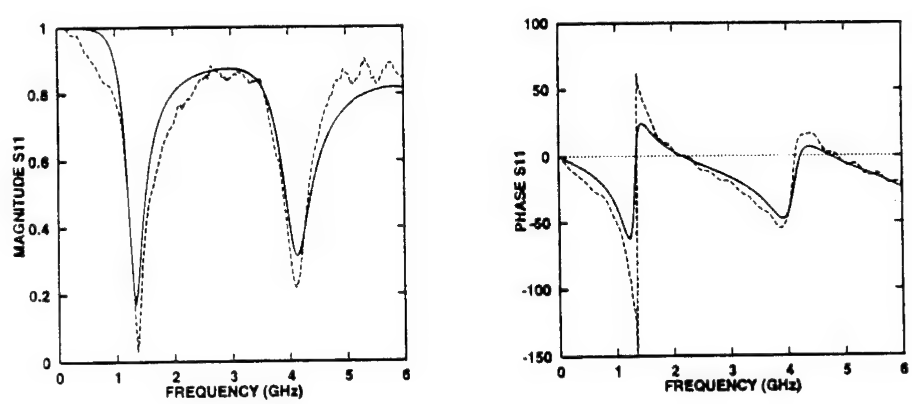
solid line: oscillator in cavity dashed line: oscillator in half-space

3 × 3 Grid Structure with Open Gaps



Driving Point Reflection Coefficient

extended unit cell

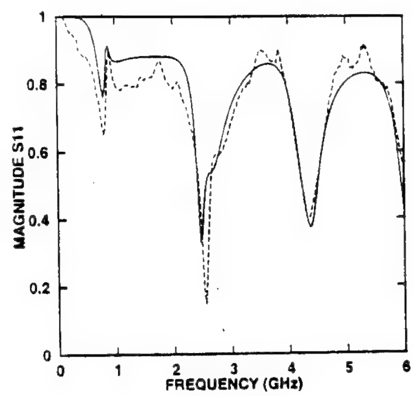


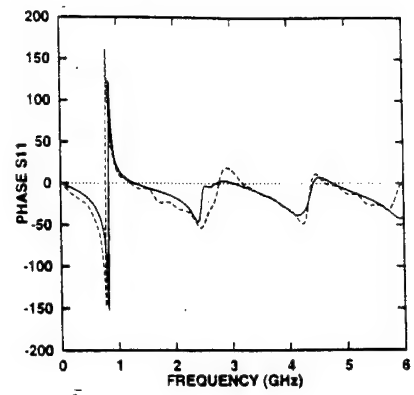
solid line: MoM simulation

dashed line: measurement

Driving Point Reflection Coefficient

3×3 grid with other gaps shorted

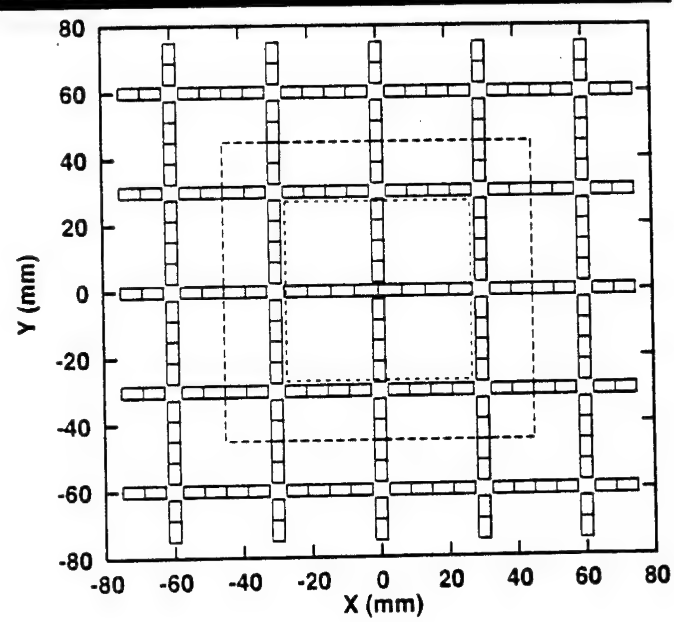




solid line: MoM simulation

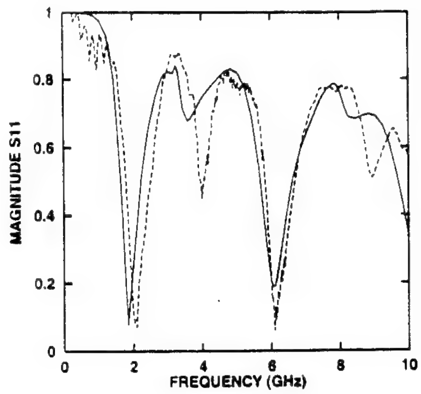
dashed line: measurement

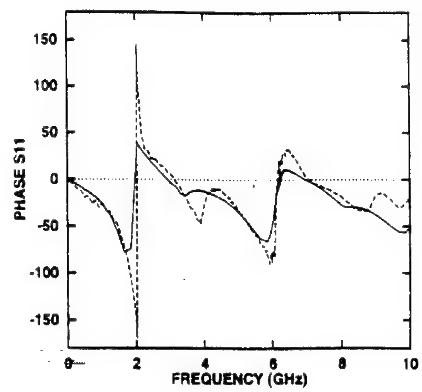
5×5 Grid Structure with Cell Sub-Division



Driving Point Reflection Coefficient

5×5 grid on a dielectric substrate in the lens system
($\epsilon_r = 2.56$, $d = 9.5$ mm, $D = 117.5$ cm)

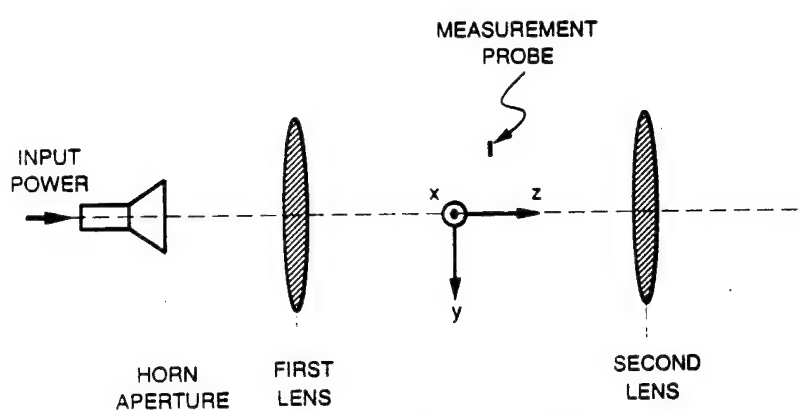




solid line: MoM simulation   dashed line: measurement

Configuration for Measuring Electric Field Intensity

X Band (8.2 GHz to 12.4 GHz)



horn aperture: 19.5 cm × 14.3 cm

lens material: Rexolite 1422 (ϵ_r=2.56)   diameter: 45.72 cm

radius of curvature: 70.49 cm   focal length: 58.74 cm

Summary

- Full-Wave Field Analysis Tools Developed for Quasi-Optical Power Combiners
- Incorporates Dyadic Green's Functions Developed for each Quasi-Optical System
- MoM Scheme Utilizing Both Spatial and Spectral Domains for Efficient Computation of the Moment Matrix Elements
- Finite Sized Structures $\Longrightarrow$ No Unit-Cell Approximations
- Accurately Predicts the Driving Point Impedance
- Simulated Results Compare Favorably with Measurements

Acknowledgments

This work was supported in part by the U.S. Army Research Office through grants DAAL03-89-D-0030 and DAAH04-95-1-0536.

Dr. James Harvey, program manager.

Hughes Electronics Quasi-Optical Power Combining Applications

Paul Greiling

Hughes Research Laboratories

Dec.4, 1995

MAR . . 199_

Missiles Seeker Radars

- Hughes Missile Systems Company is a major supplier of high performance missiles
- Next generation of Hughes missiles will have more accuracy and longer range, all for a lower cost
- Critical to this next generation missile seeker is a higher power radar operating at a higher frequency

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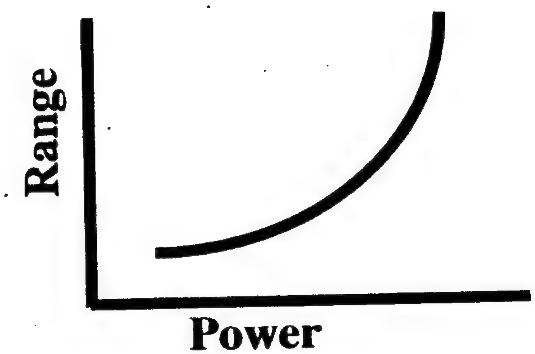
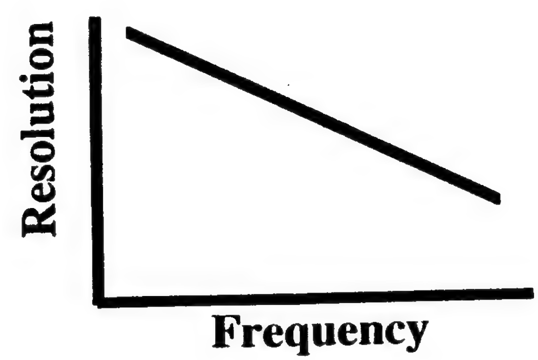
Missile Seeker Radar

- Range increases proportionally to the inverse fourth power of the output power
- Resolution improves linearly with the operating frequency





Missile Seeker Radar Requirements

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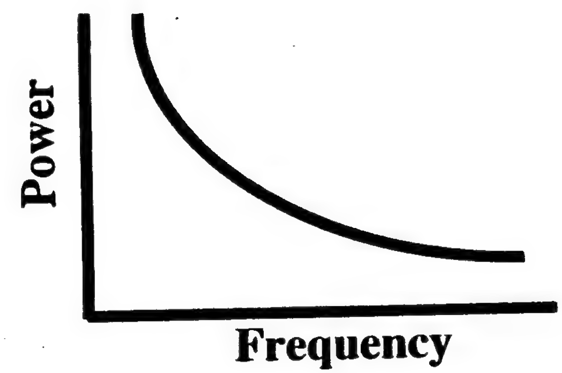
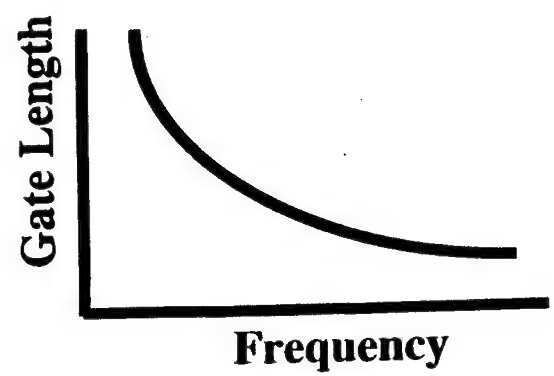
- Need to increase operating frequency from Ka-band to W-band to D-band
  - New HEMTs
  - Sub-quarter micron gate lengths
- Need to increase output power to watts at millimeterwave frequencies
  - Higher frequency and breakdown voltage devices
  - Power combining techniques

Millimeterwave Device Technology

- Device output power decreases with increasing frequency
- Higher frequency of operation requires shorter gate lengths





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Millimeterwave Technologies

- New epitaxial materials systems are required for high power and frequency devices---InP & Sb
- Extremely short gate lengths are required for high frequency operation---<0.1 micron
- Power combining techniques are required for high output power levels---quasi-optical

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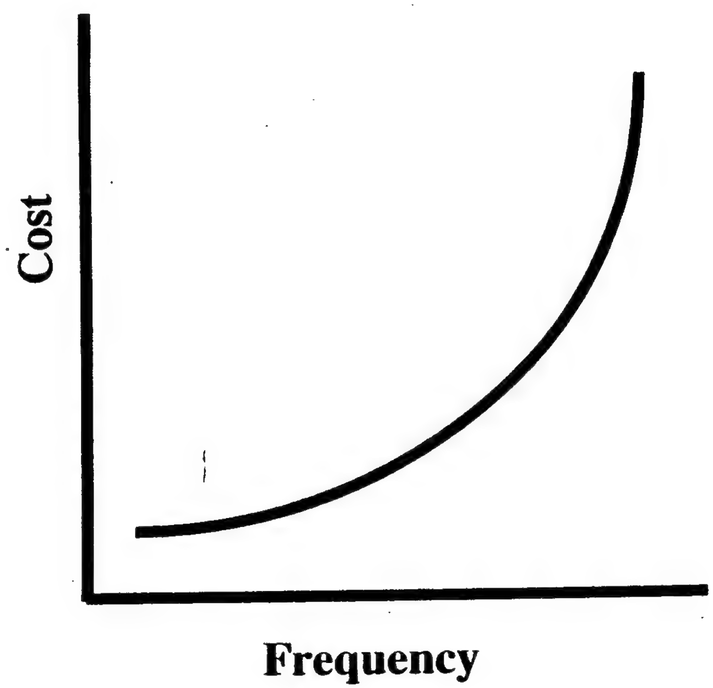
Radar Cost Drivers

- Cost of high power, high frequency radar is prohibitive due to:
  - semiconductor cost
  - yield
  - power cell size
- Need to combine many low power, low cost devices to achieve high power, high frequency radar

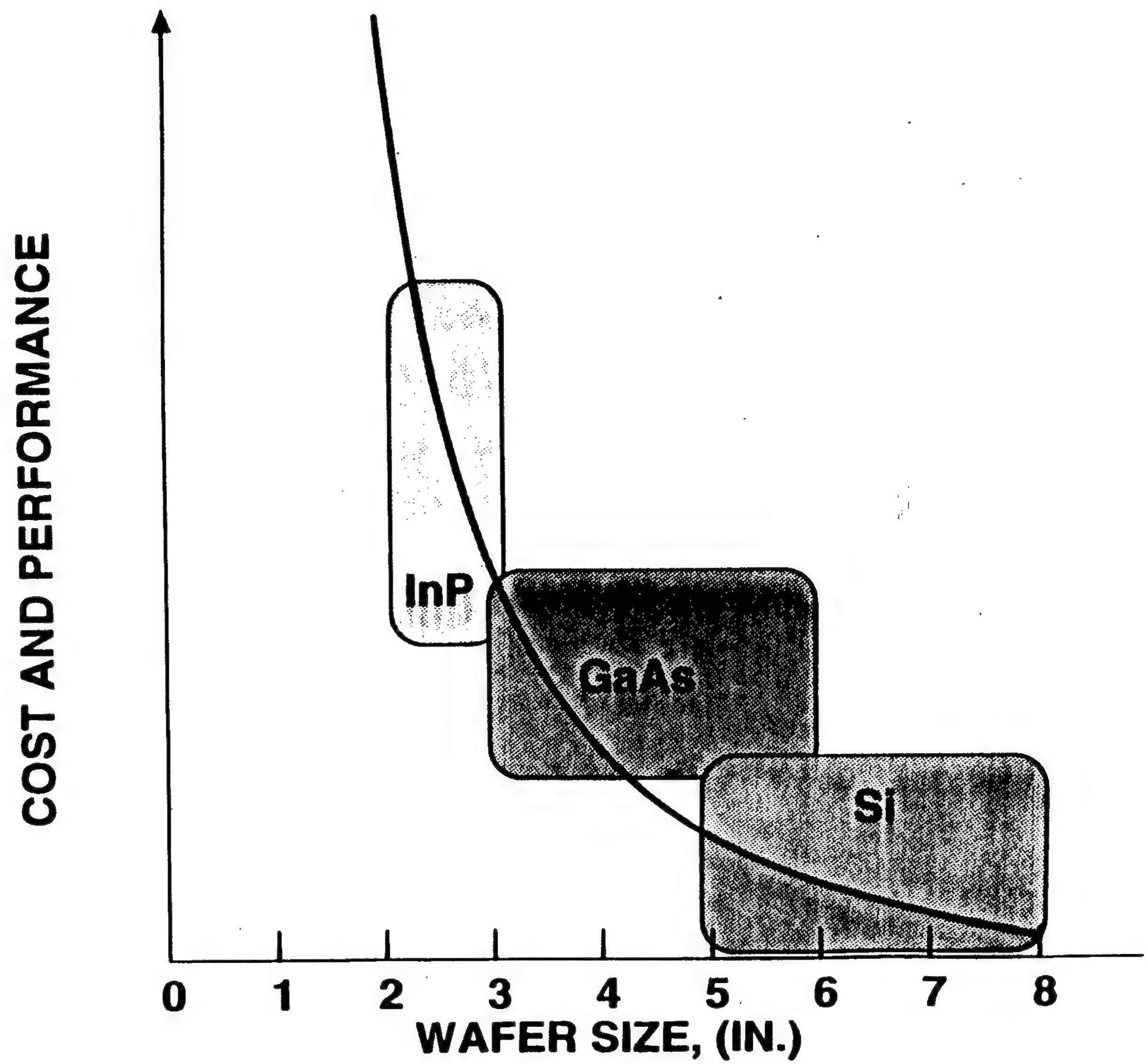


Quasi-optical power combining of low cost cells

TECHNOLOGY COST AND PERFORMANCE

GM HUGHES ELECTRONICS

9125-02-014



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COMPARISON OF MICROWAVE INTEGRATED CIRCUIT APPROACHES

GM HUGHES ELECTRONICS

9425-02-016

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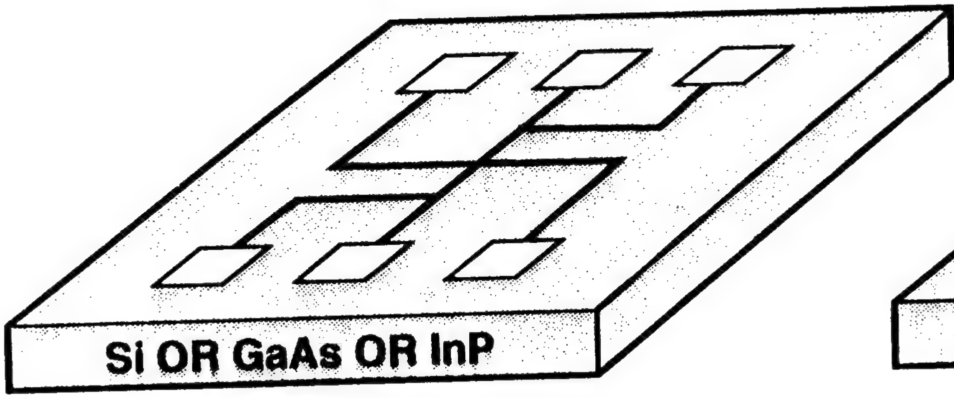

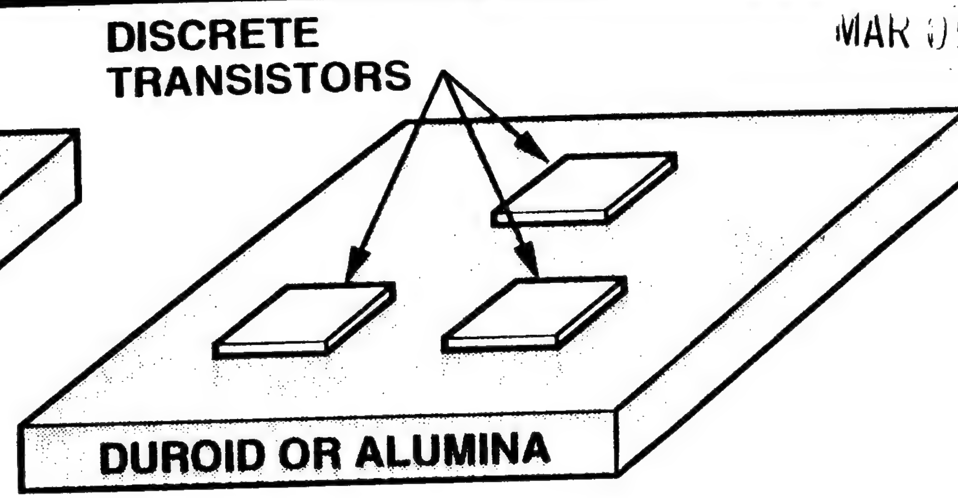

MONOLITHIC MICROWAVE IC

ADVANTAGES

- LOW ASSEMBLY COSTS

DISADVANTAGES

- LOW YIELD
- HIGH COST FOR NEW TECHNOLOGIES

HYBRID MICROWAVE IC

ADVANTAGES

- LOW COST FOR LOW COMPLEXITY
- DIFFERENT DEVICE TYPES FOR OPTIMIZED PERFORMANCE

DISADVANTAGES

- HIGHER ASSEMBLY COSTS

FLIP-CHIP GRID AMPLIFIER/OSCILLATOR

HUGHES ELECTRONICS

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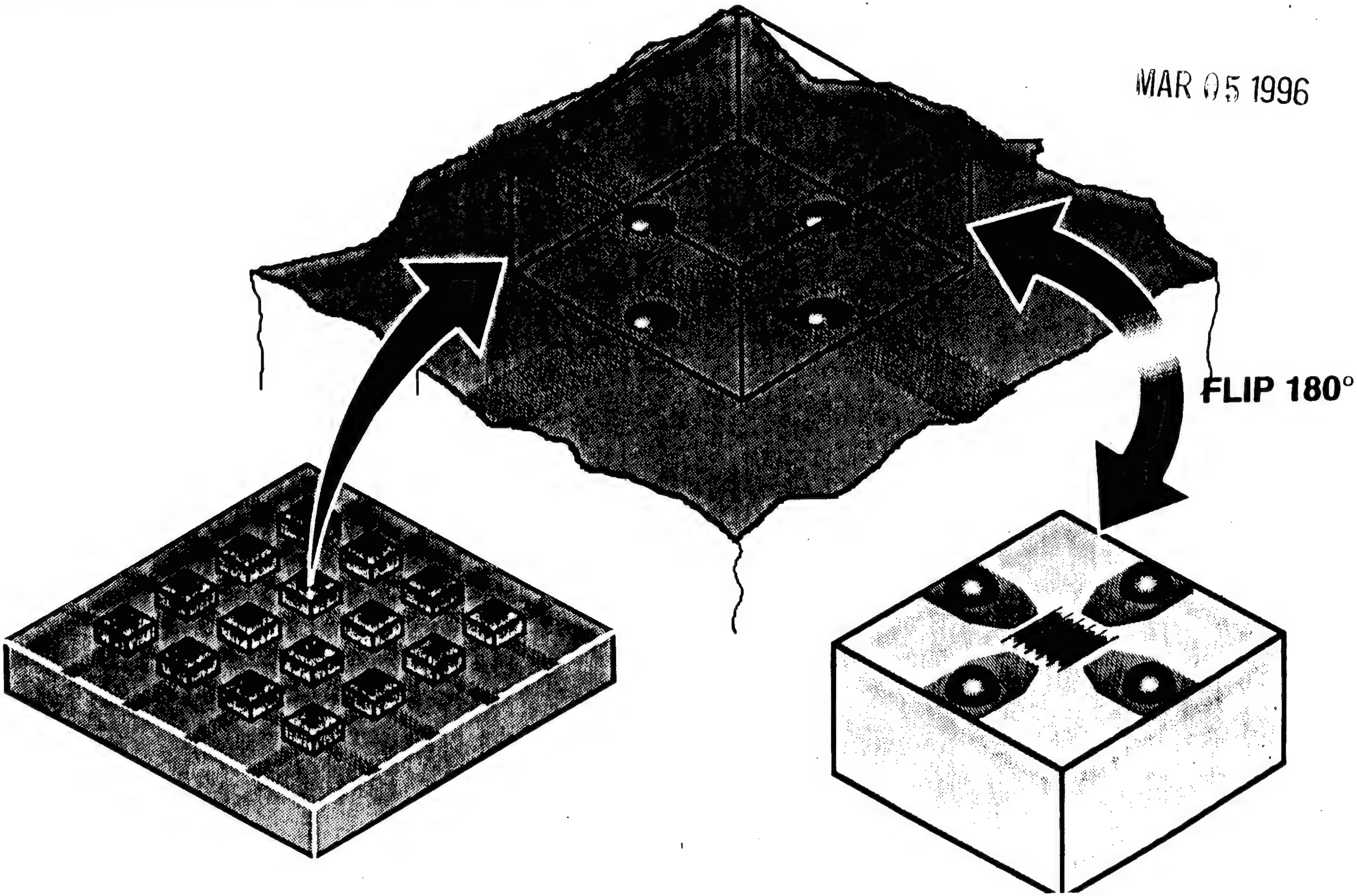

Program Goals

- Short Term---Yr 2000
  - 10 Watts @100 GHz for $1000
- Long Term---Yr 2005
  - 100 Watts @ 100 GHz for $100

Conclusions

- Radar resolution and range must be increased
- Costs must be reduced in the next generation of missile seeker radars
- Trade off of power cell size vs. costs must be performed
- Quasi-optical power combining is required to achieve the desired power levels

mmWave Plane Wave Amplifiers

1996

There are today three monolithic Plane Wave Amplifiers under development at Rockwell Science Center

(a) Grid Amplifier at 40-44 GHz

Uses orthogonally polarized input dipole antennas and output dipole antennas ; developed with Caltech

(b) Slot-Patch PWA at 40-44 GHz

Uses Slot antennas in ground plane of microstrip for input and patch antennas on microstrip surface for output

(c) Folded Slot PWA at 40-44 GHz

Uses orthogonal pairs ofFolded Slot antennas for input and output developed with UCSB

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THESE ARE ALL TRANSMISSION TYPE PWAs

Monolithic Grid Amplifier

BCR0816A.041395

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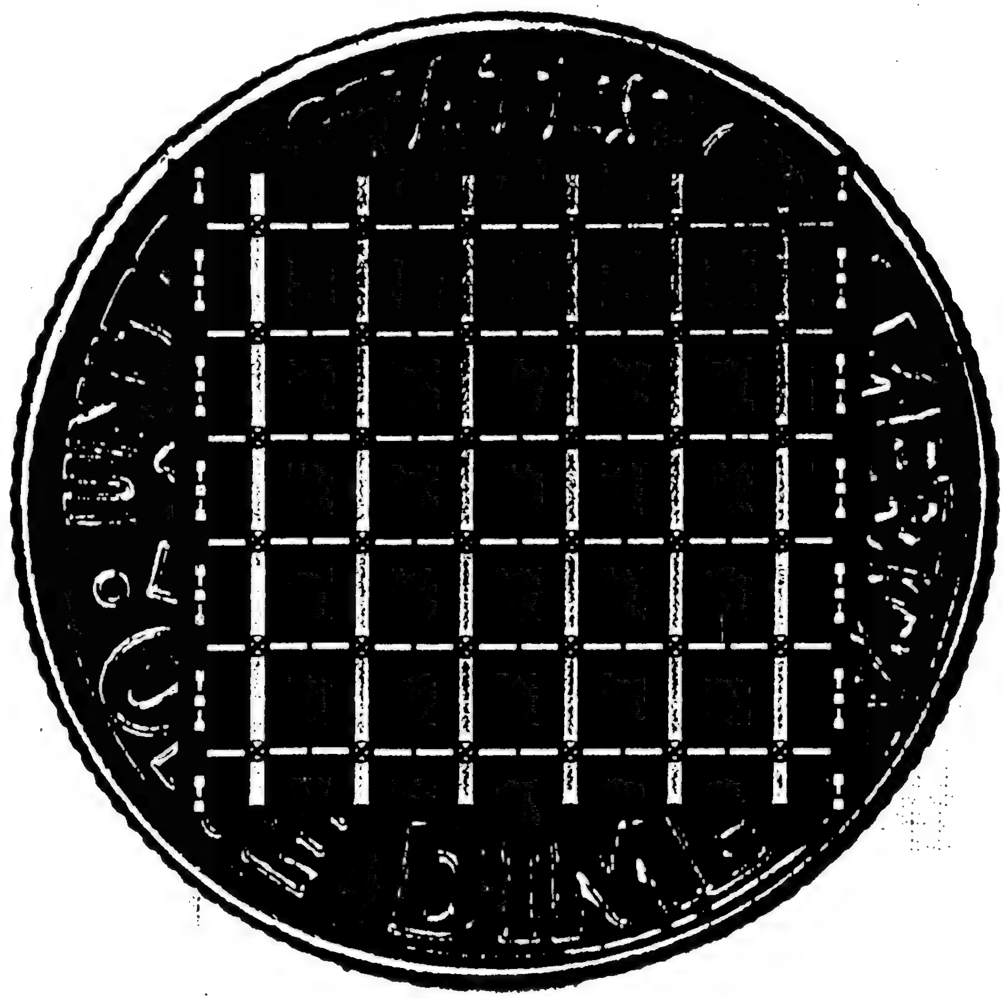

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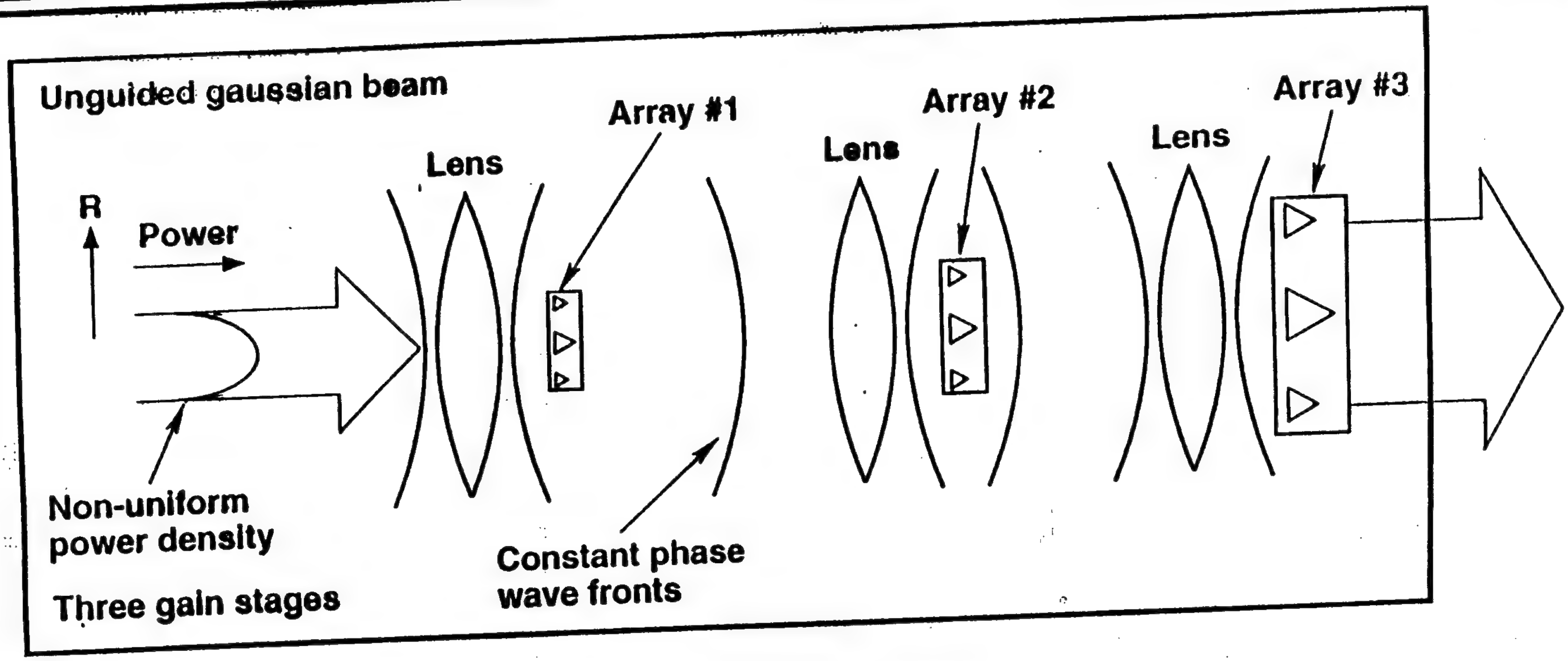
Transmission Amplifiers: Gaussian Power Beam

SC.1125E.040494



Type TGPD1: Power density varies across beam width

Radially non-uniform device sizes to cope with radial power density change

Amplifier diameter increases to accomodate more power

Gaussian optic lenses required for wavefront management

Rockwell International
Science Center

mmWave Plane Wave Amplifiers

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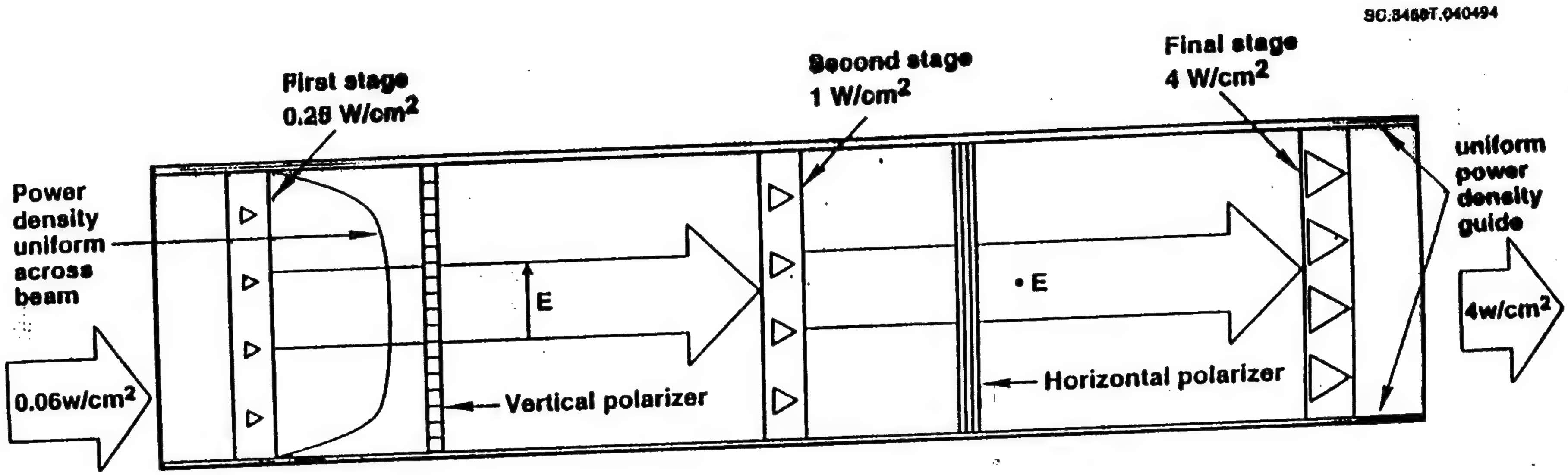
A Concept figure illustrating the Guided Wave PWA system



Waveguide is designed to maintain a uniform cross section power density. Three stages of amplification are cacaded in this conceptual sketch

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PWA Design

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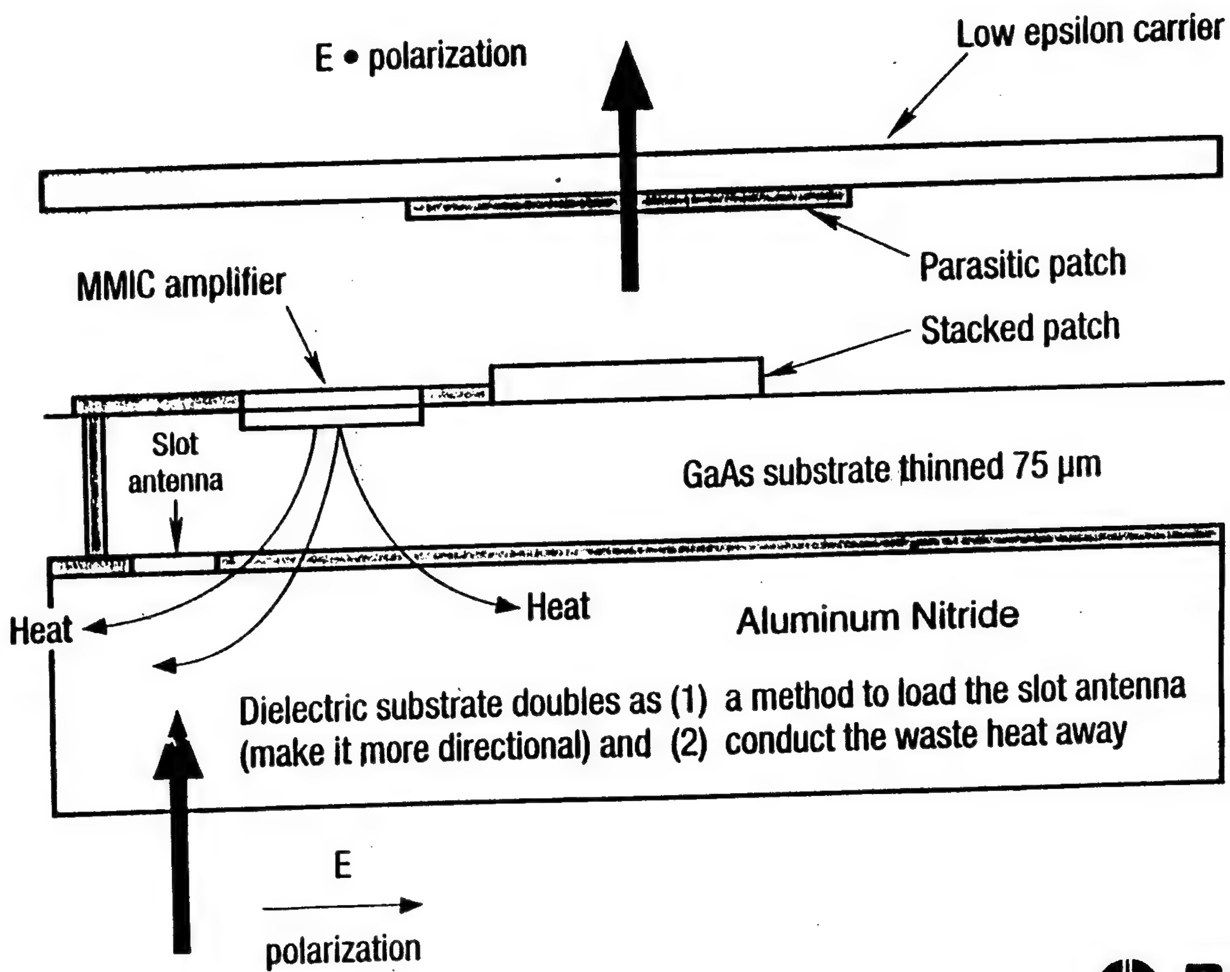

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Plane Wave Amplifier Chip
Mounted on an Aluminum Nitride Carrier

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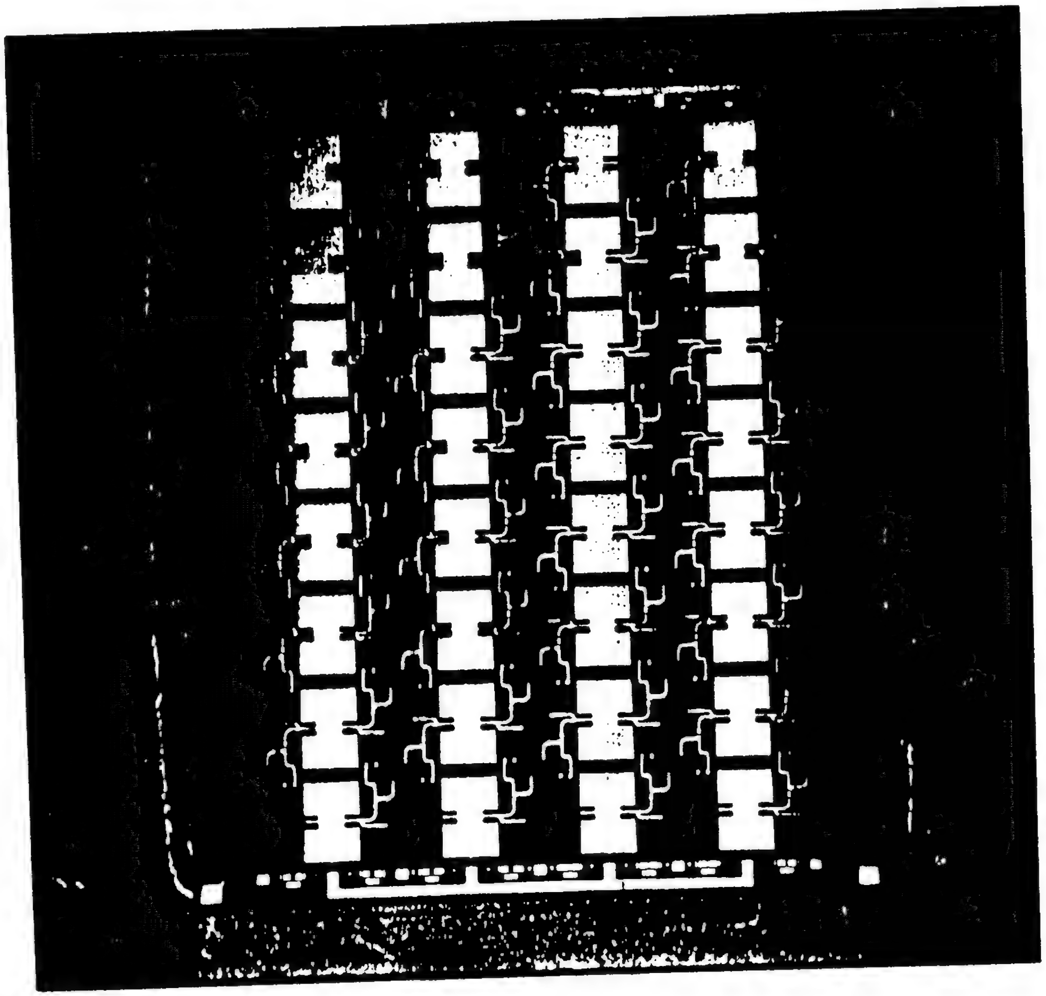

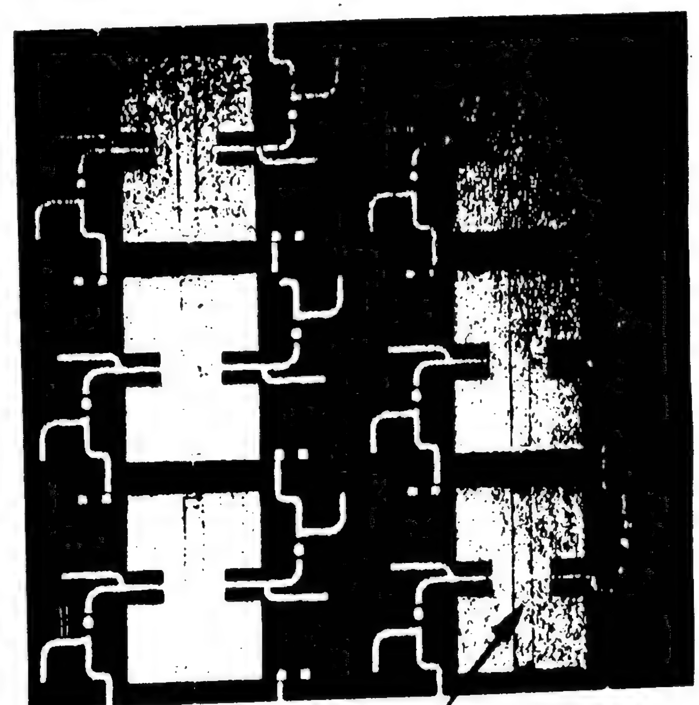

• 44 GHz DWA CELL

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SCP.0935A090595

Waveguide Test Fixture for mm Wave Plane Wave Amplifier

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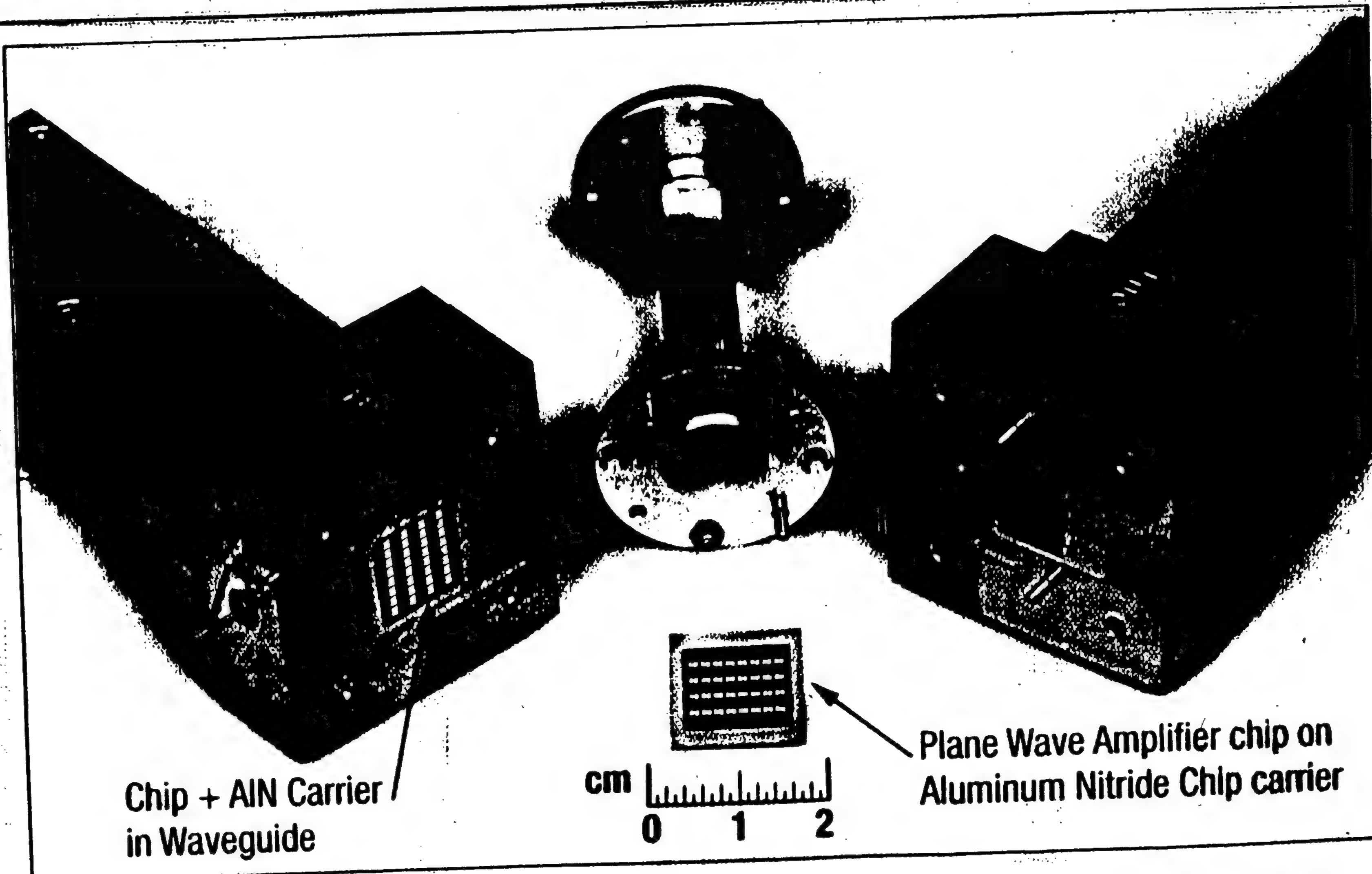

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Waveguide Test Fixture for mm Wave Plane Wave Amplifier

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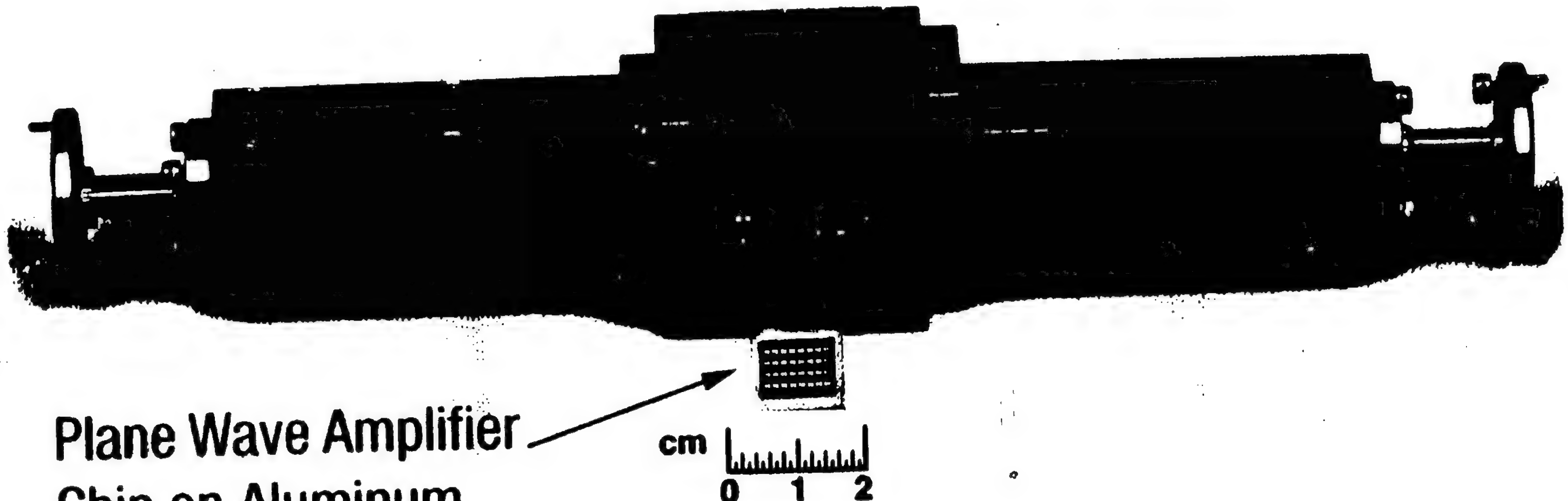

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SCP.0928A.081595

44 GHz Quasi-Optic PHEMT Amplifier

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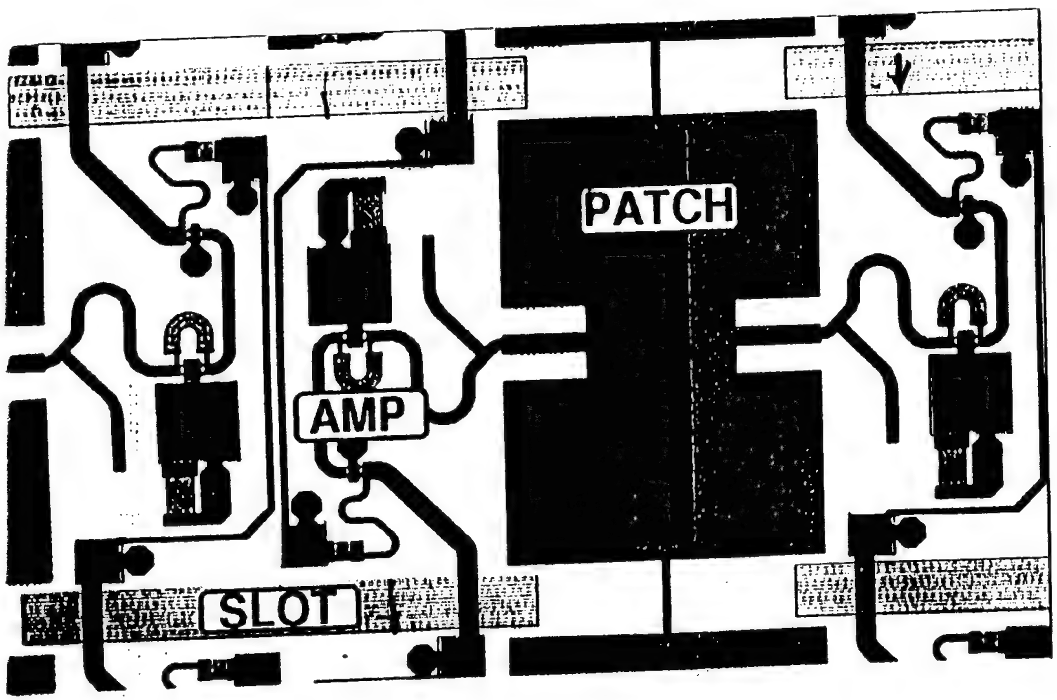

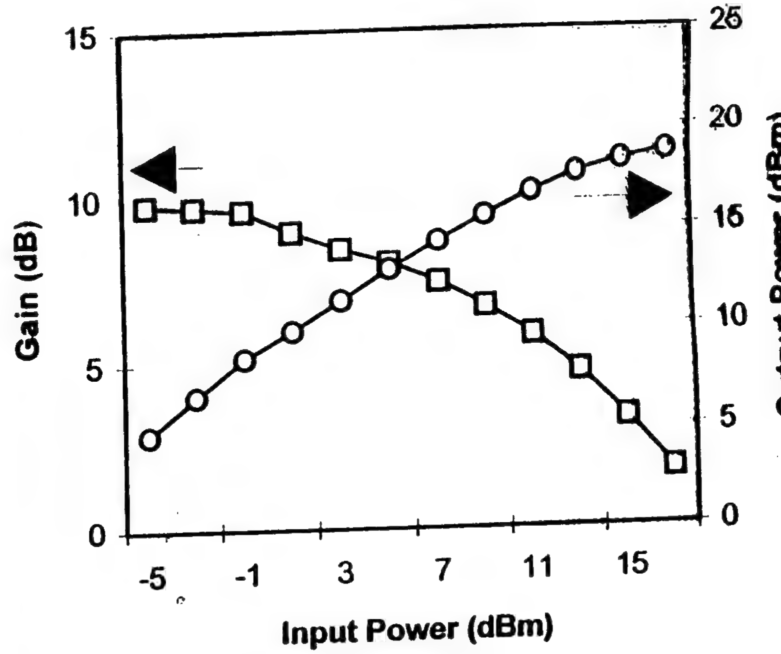

(Power characteristics of one cell)

- Direct-coupled 2-stage design
  - compact design and good stability

- Small-signal gain > 8 dB
- Total output power ~ 2.2W

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PHEMT PWA Gain and Return Loss

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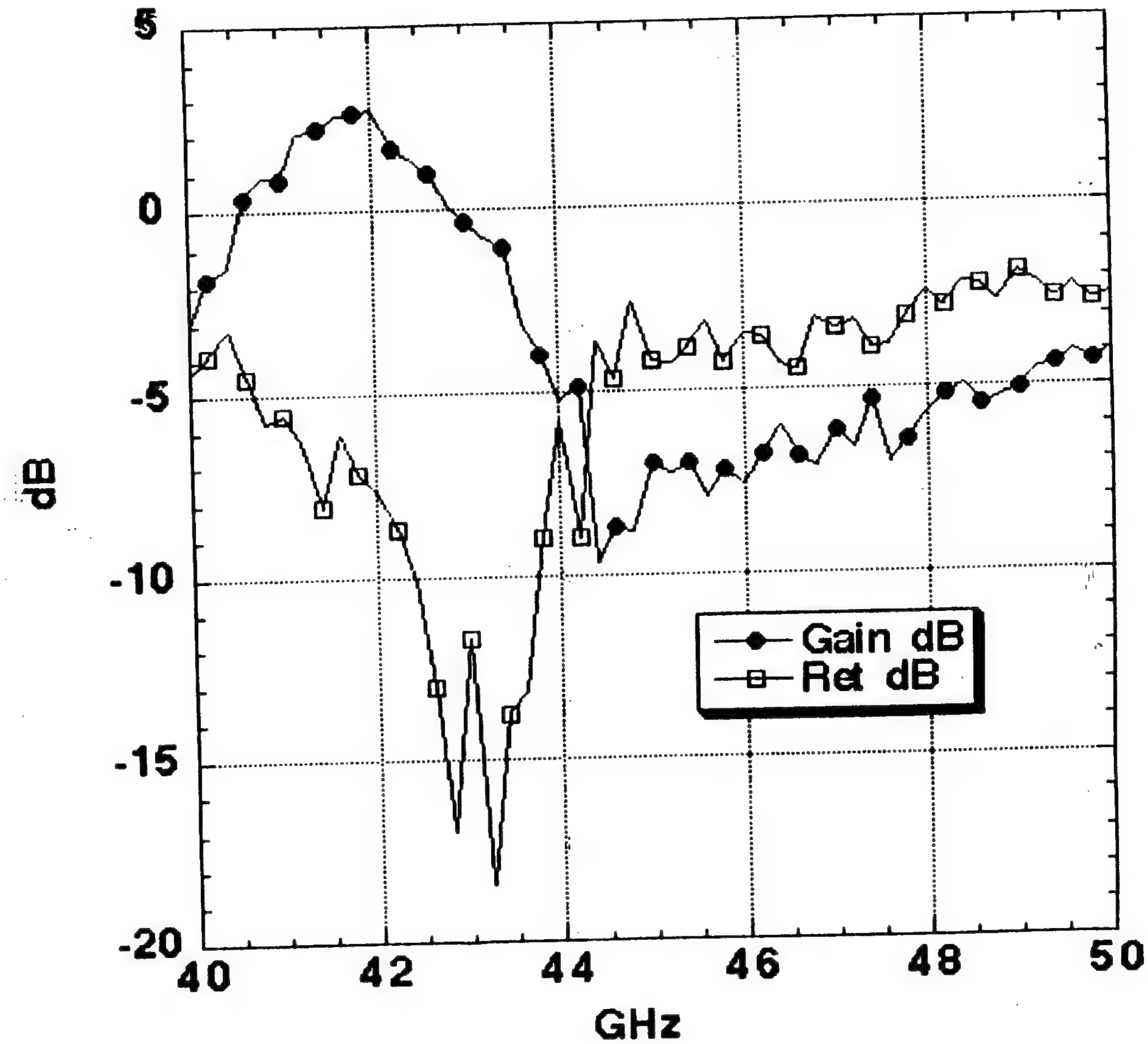

Max. Output .25W

Measurement is uncorrected for fixture loses. (flange to flange)

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eas 11/14/95 20

mmWave Plane Wave Amplifiers

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NEXT STEPS

- THE OPTIMUM APPROACH WILL NOT INCLUDE MICROSTRIP PATCH ANTENNAS

  IT WILL BE BASED ON ORTHOGONAL SLOT ANTENNAS FOR INPUT AND OUTPUT BACKED UP BY NEW TECHNOLOGY TO ENHANCE ANTENNA PERFORMANCE:-- PHOTONIC BANDGAP SUBSTRATES

- THE NEW SLOT ANTENNAS MAY BE "FOLDED SLOT ANTENNAS"

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mmWave Plane Wave Amplifiers

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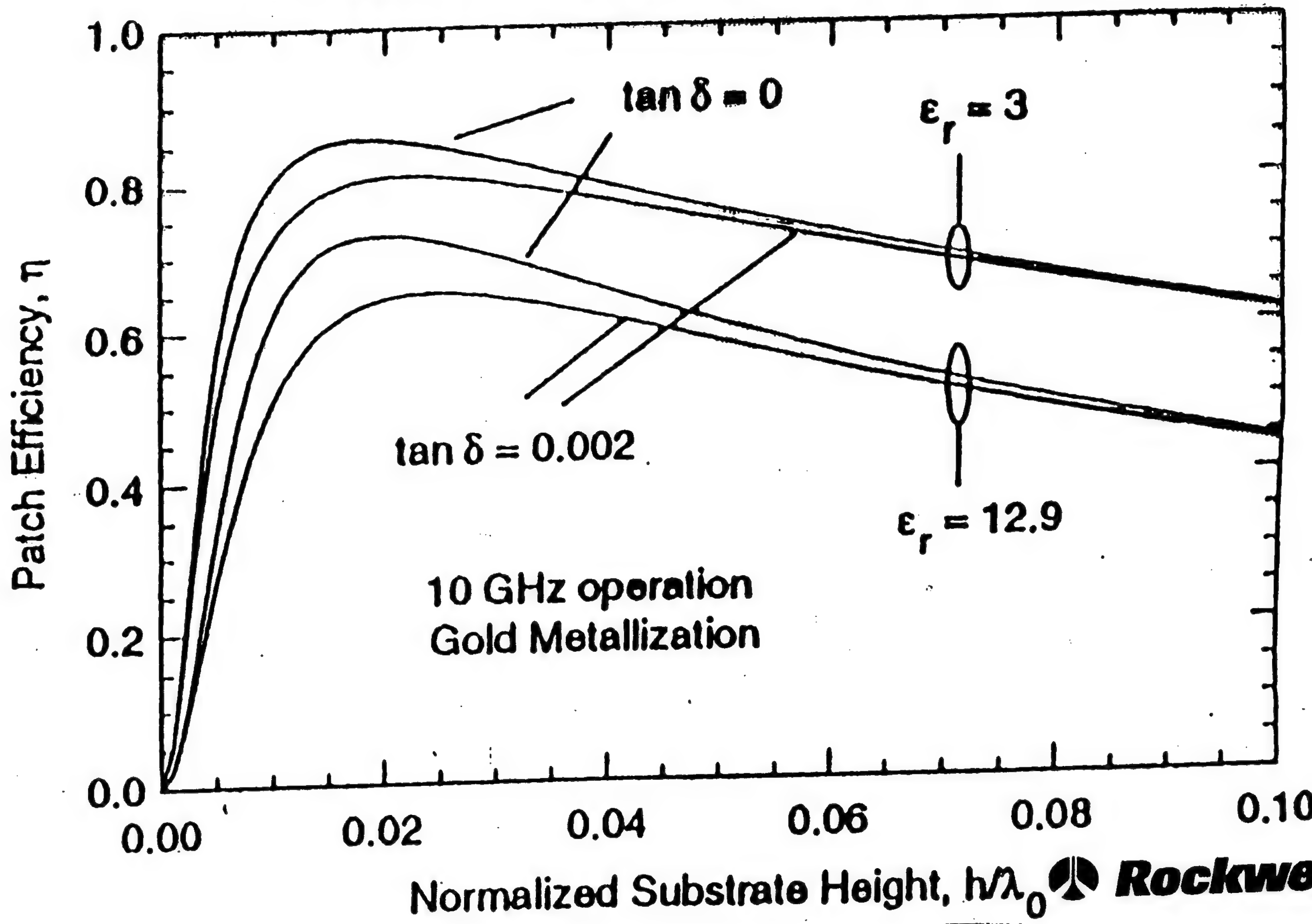

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Example: Patch antenna

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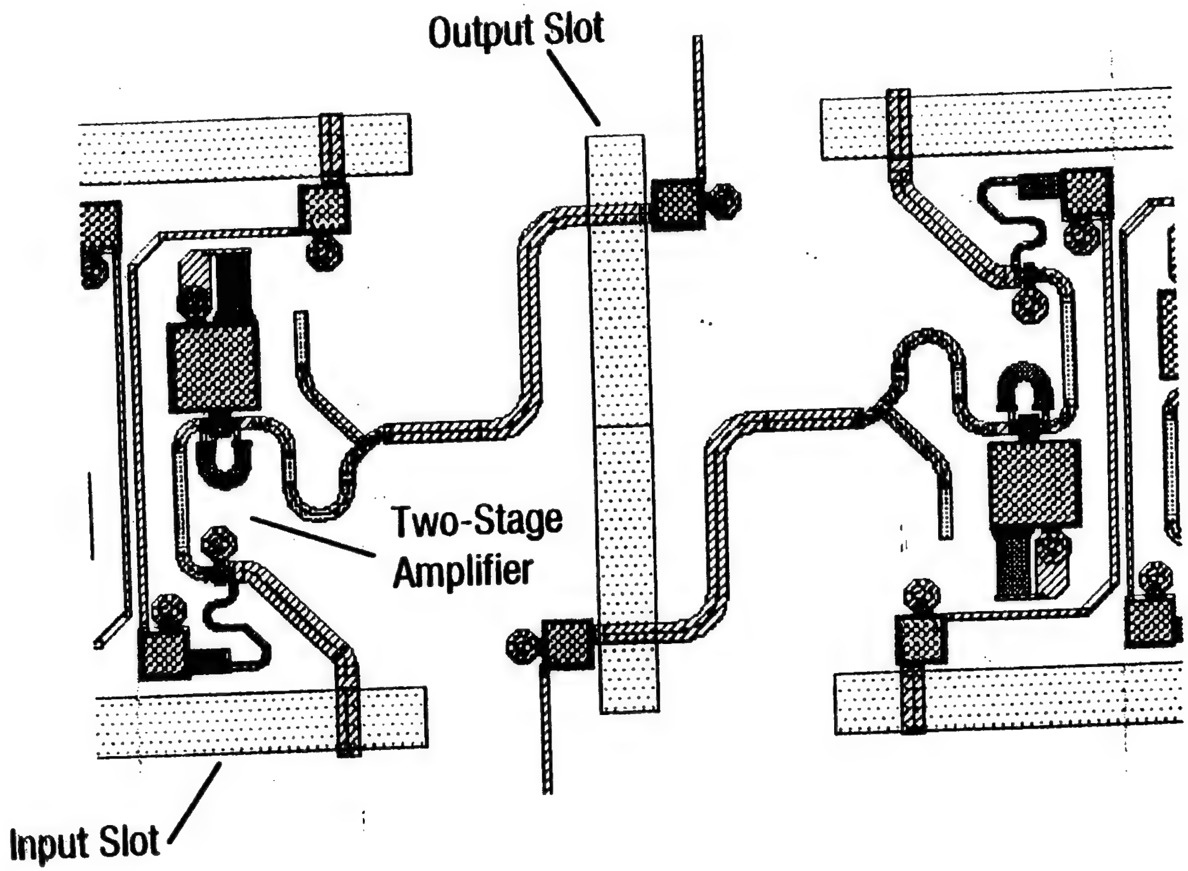
Slot - Slot Unit Cell



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Aluminum Oxide Two Dimensional PBGS
Fabricated Using LOM Rapid Prototyping Technique

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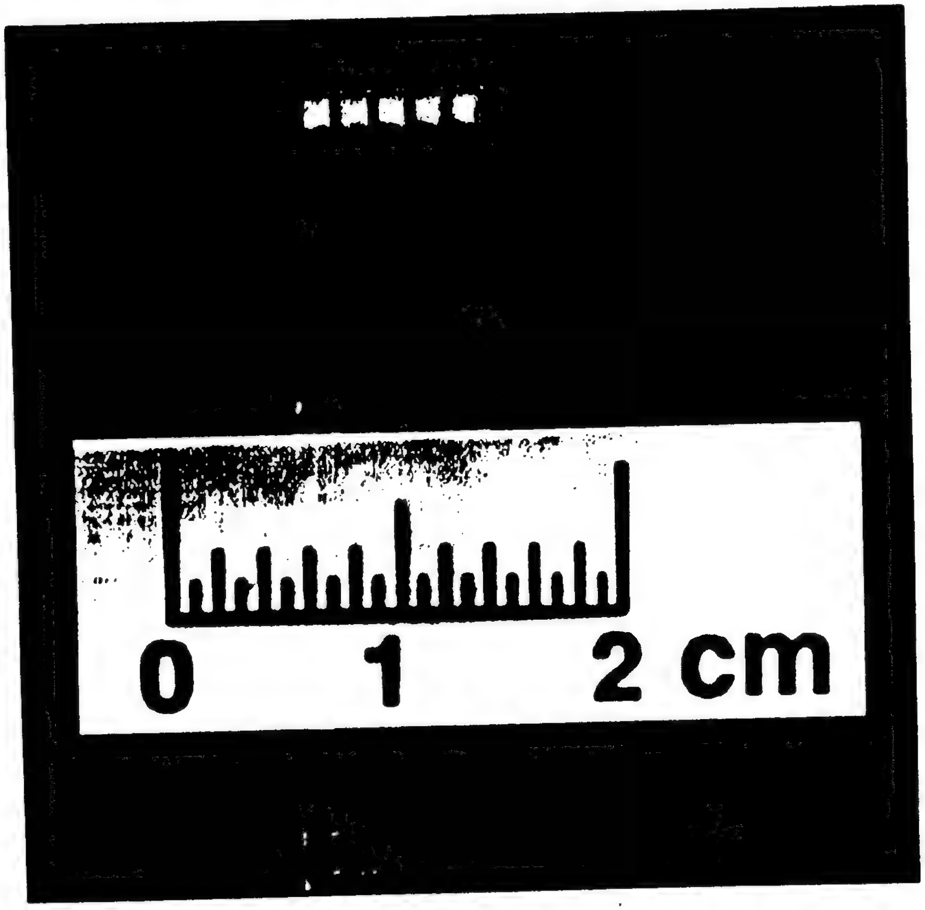

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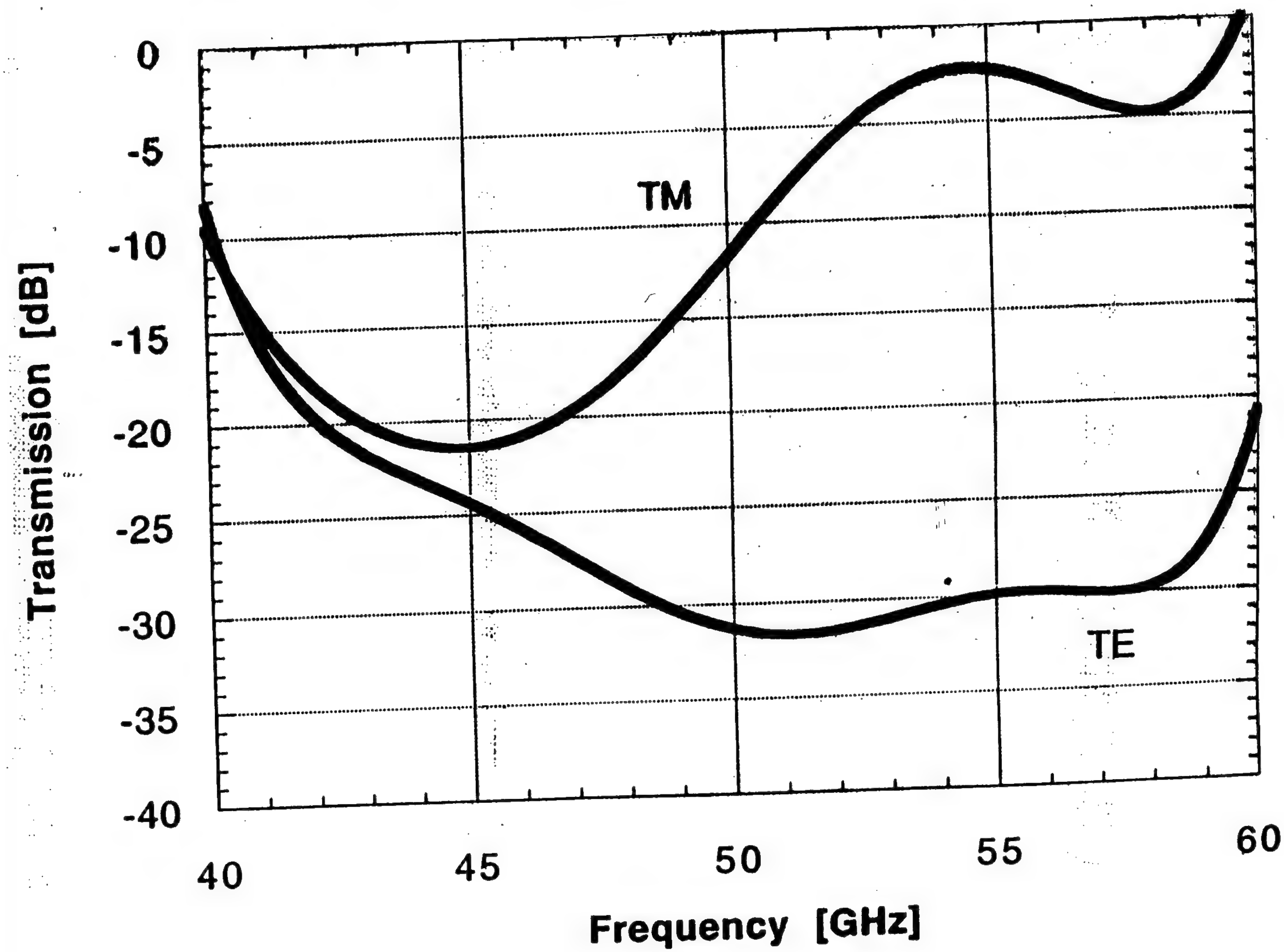
SCP.0940A 091395

Tranamission through Aluminum Oxide PBGS



mmWave Plane Wave Amplifiers

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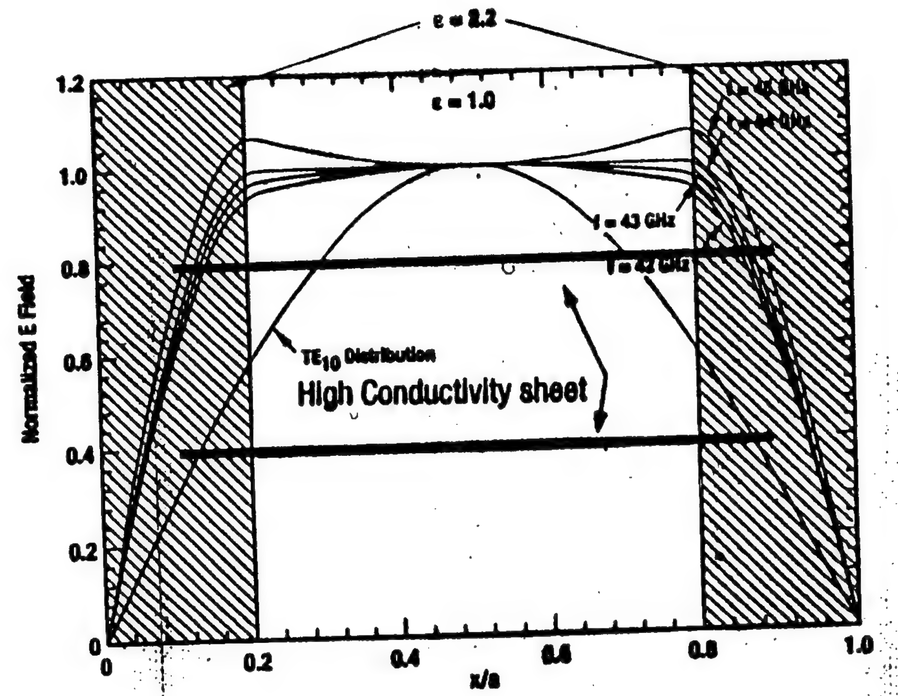

The oversized waveguide must have dielectric loading to force field uniformity . Mode control is supplied by properly placed conductor sheets

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QUASI OPTICAL POWER COMBINING

GOALS:

- Solid-state quasi-optical power amplifiers/sources for 10-100 watts 35 to 100 GHz

- Predictive modeling of device/circuit performance based on full wave analysis of device/antenna array

- Improvement of device (PHEMT) efficiency enabling up to 100 watts at W-band

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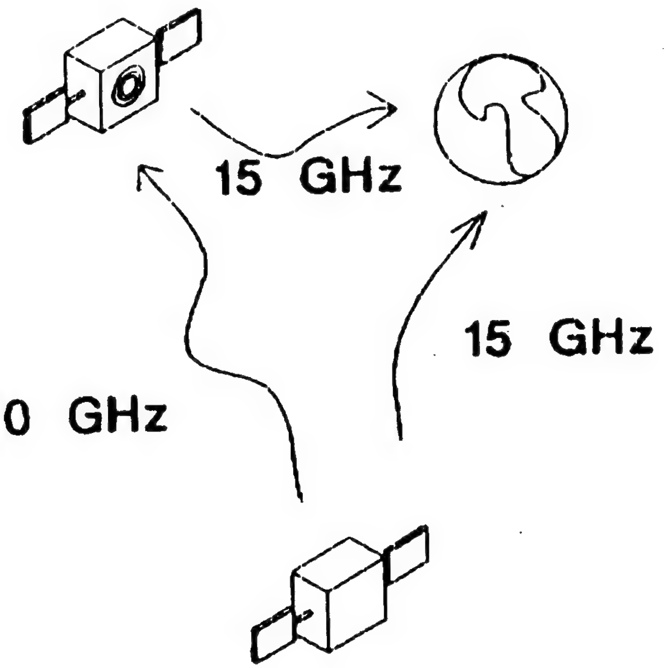
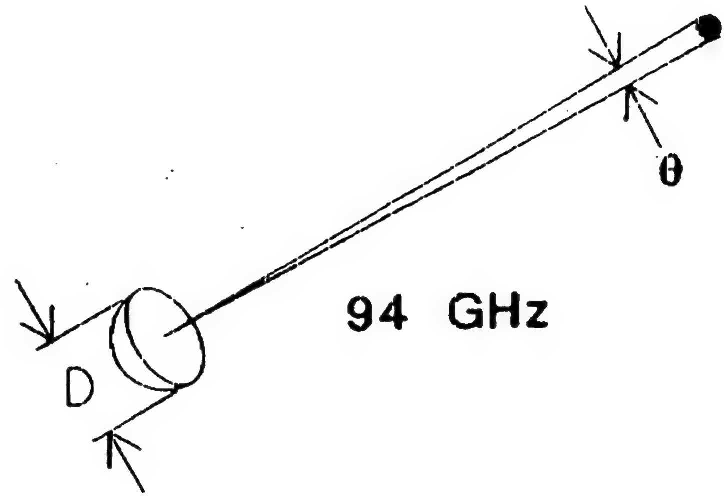
HIGH POWER MILLIMETER WAVE APPLICATIONS





Path Loss:

$$P_R = P_R G_T G_R \left(\frac{4 \pi r}{\lambda} \right)^2$$

Inter-Sattelite
Communication

Rayleigh Criterion:

$$\theta_{MINIMUM} = 1.22 \frac{\lambda}{D}$$

Hi Resolution
Radar

EXAMPLE OF QUASI-OPTICS

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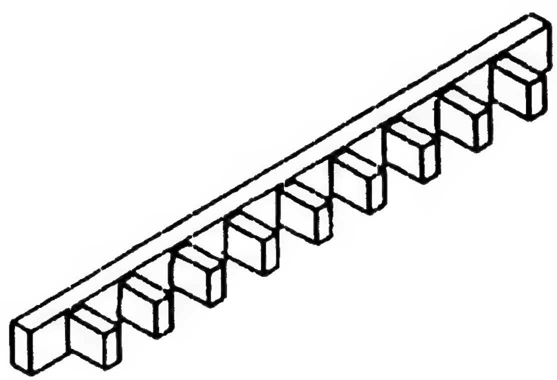
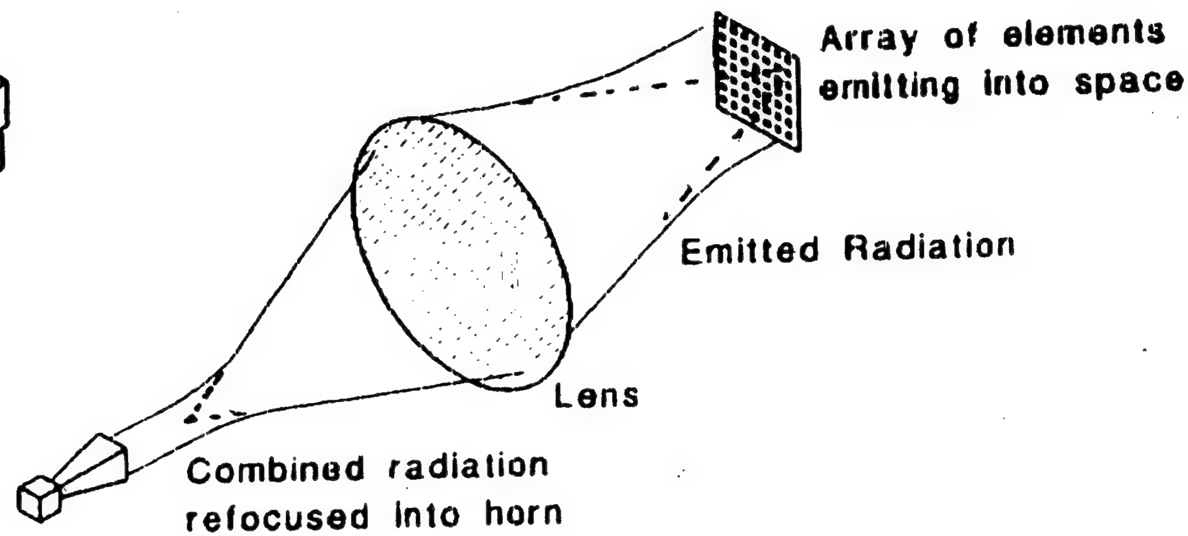
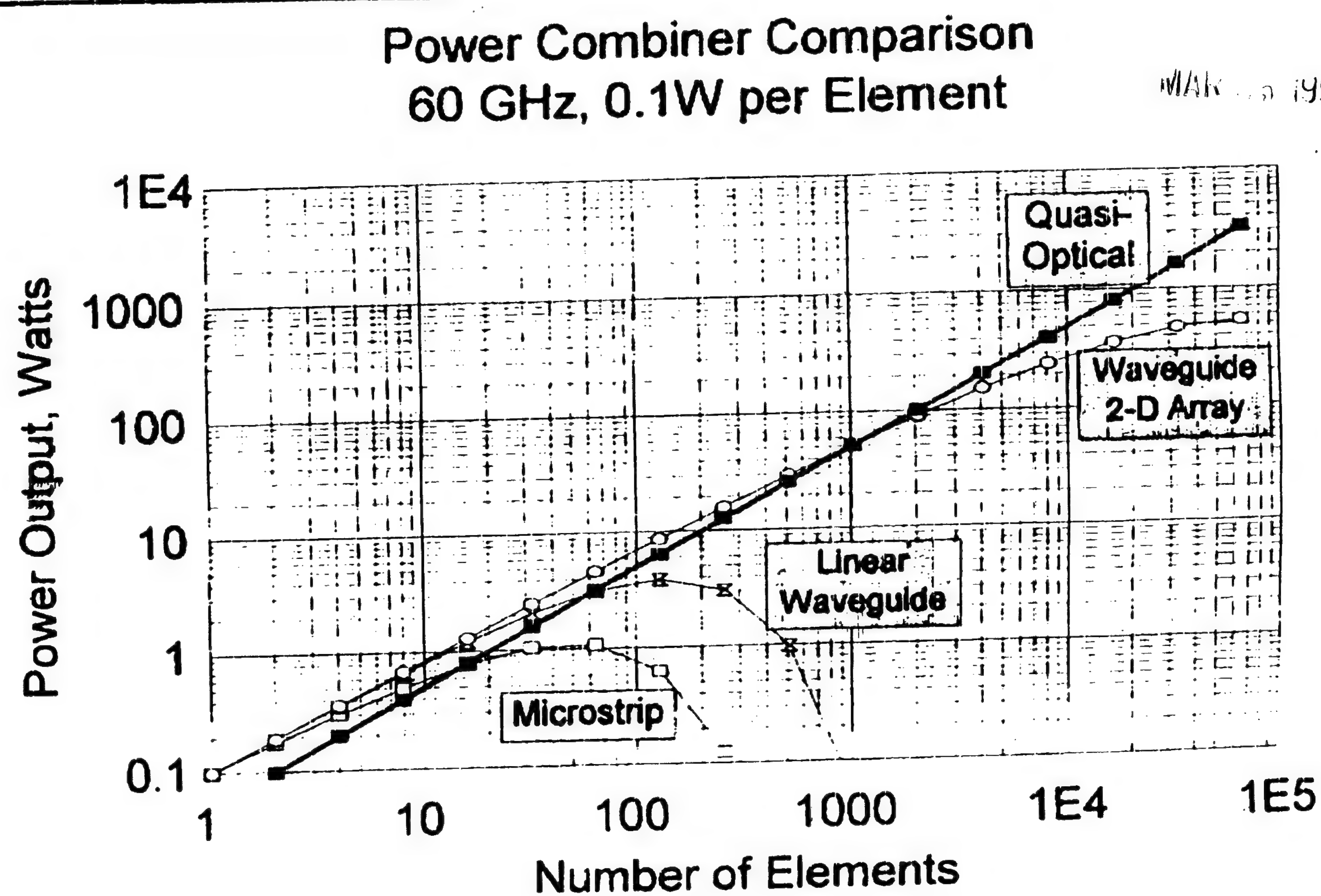
Waveguide Combiner



Quasi-Optical Combiner





Power Combiner Comparison
60 GHz, 0.1W per Element
Power Output, Watts
1E4
1000
100
10
1
0.1
1
10
100
1000
1E4
1E5
Number of Elements
Quasi-Optical
Waveguide 2-D Array
Linear Waveguide
Microstrip

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RADAR SYSTEM REQUIREMENTS AFFECTING QUASI-OPTICAL POWER COMBINING DEVICES

WILL CARAWAY

4 DEC 95

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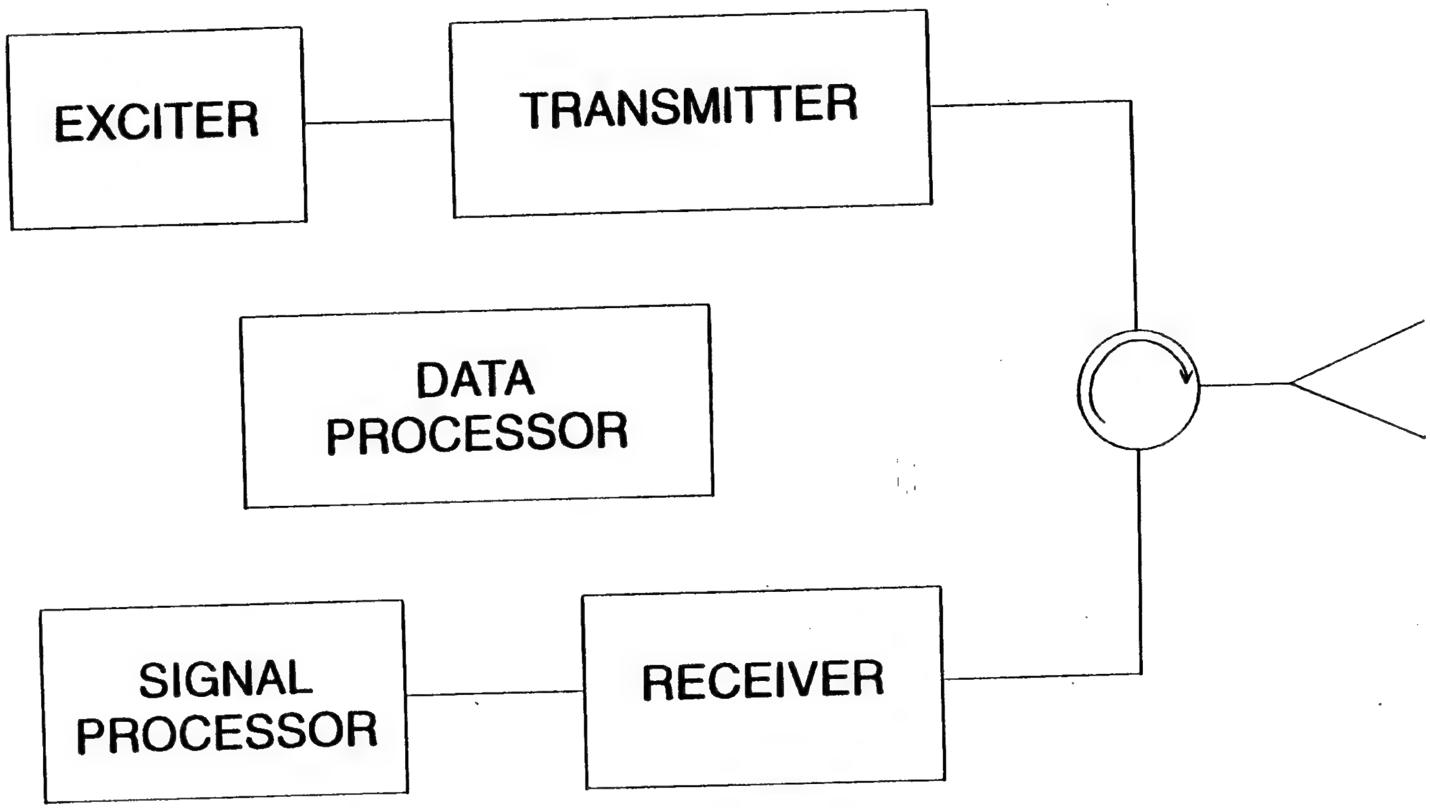
PULSE RADAR BLOCK DIAGRAM



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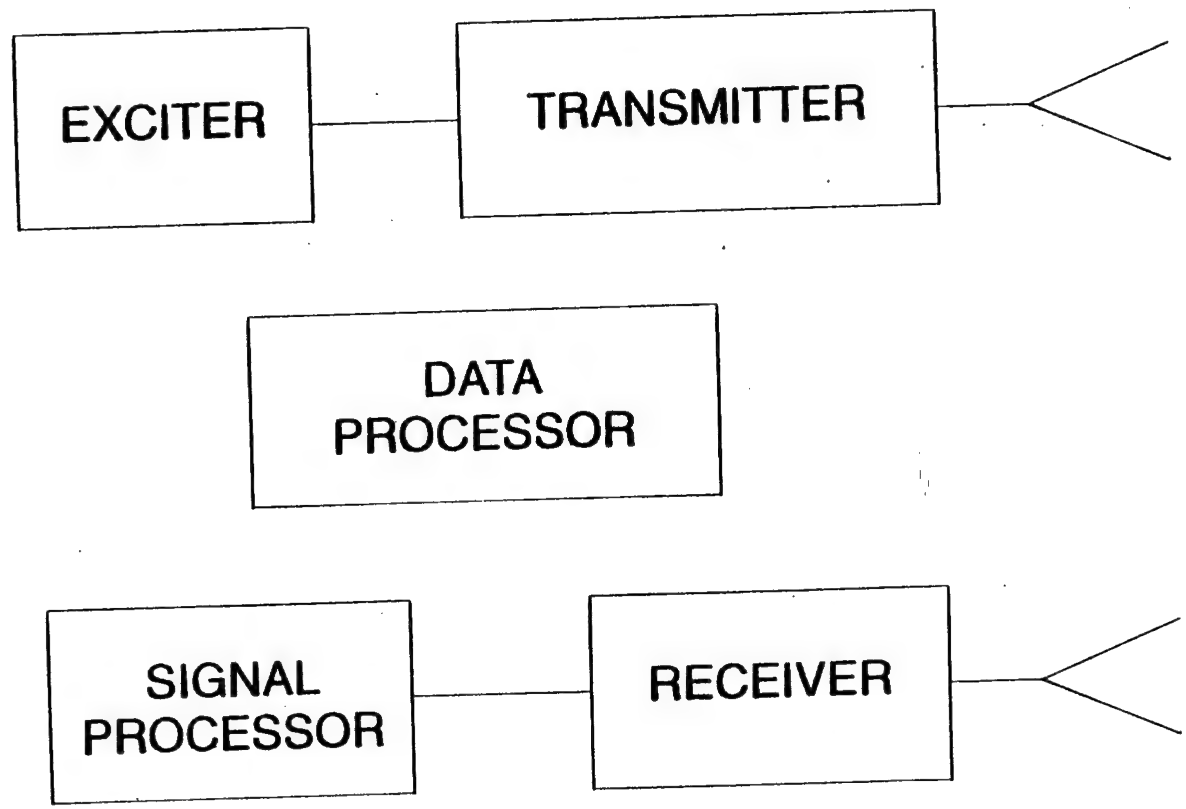
CONTINUOUS WAVE (CW) RADAR BLOCK DIAGRAM



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GROUND BASED RADAR TRANSMITTER REQUIREMENTS

- TRANSMIT FREQUENCY: 1 - 16 GHz
- OPERATIONAL BANDWIDTH: 200 MHz - 5 GHz
- INSTANTANEOUS BANDWIDTH: 2 MHz - 1 GHz
- TRANSMIT POWER: 1 W - 1 MW
- PHASE NOISE: -50 - -135 dBc/Hz @ 10 kHz (Absolute)
- WAVEFORMS: PULSE, BI-PHASE MODULATED, LINEAR FM, STEPPED FM

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RADAR SEEKER TRANSMITTER REQUIREMENTS

- TRANSMIT FREQUENCY: 10 - 95 GHz
- OPERATIONAL BANDWIDTH: 200 - 500 MHz
- INSTANTANEOUS BANDWIDTH: 2 - 500 MHz
- TRANSMIT POWER: 1 - 900 W
- PHASE NOISE: < -120 dBc/Hz @ 10 kHz (Absolute)
- WAVEFORMS: PULSED, LINEAR FM, STEPPED FM

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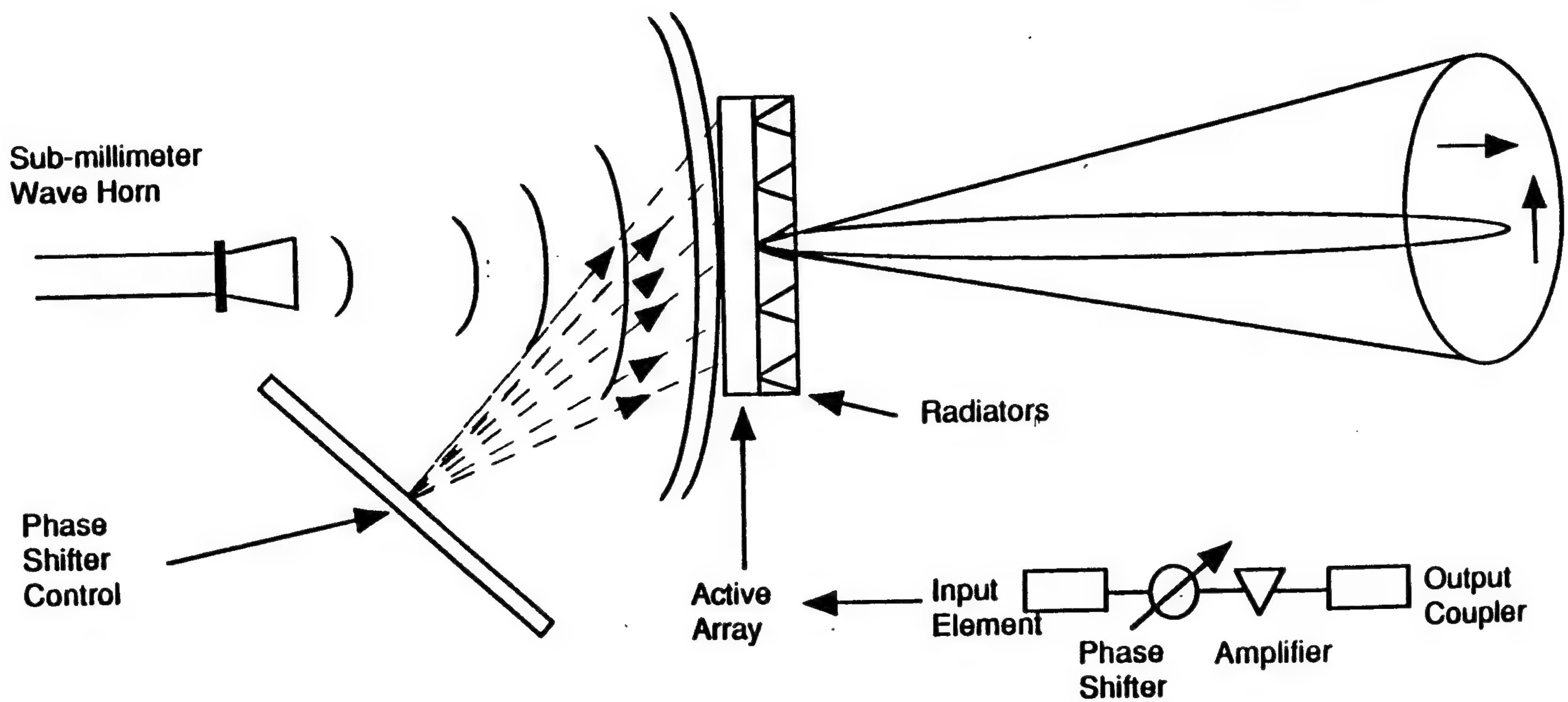
Quasi-Optical Scanned mmW Antennas



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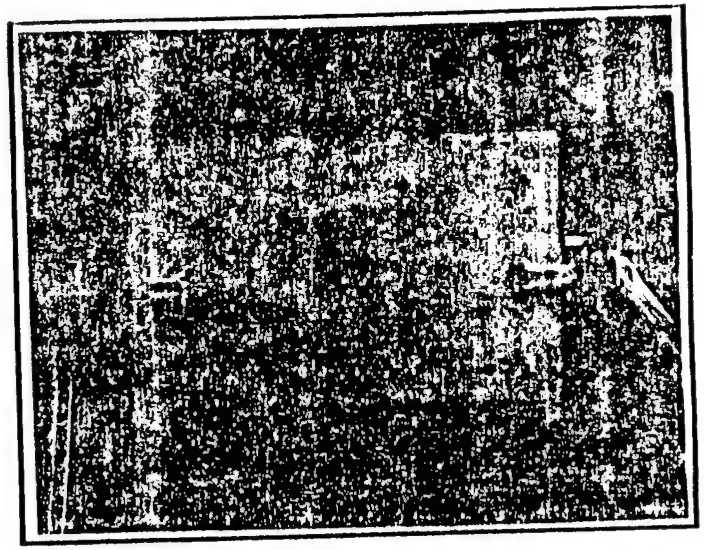
Radiatively Coupled Oscillator Arrays

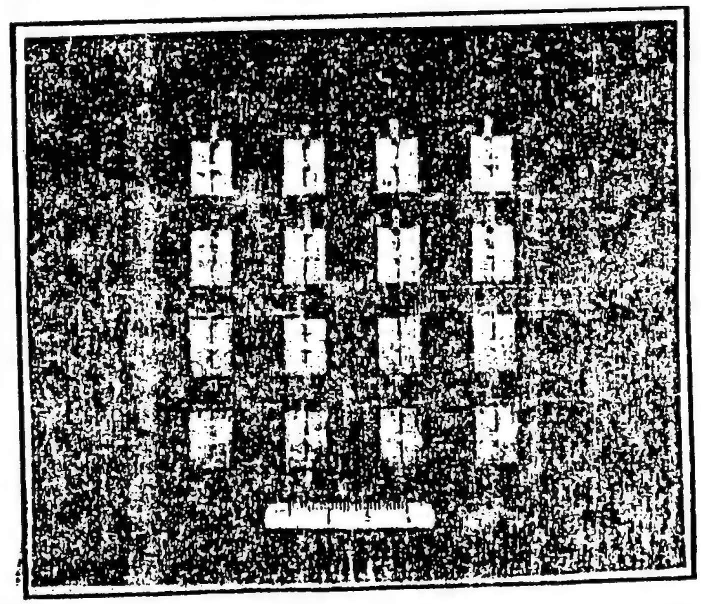
Simple patch-antenna based oscillators synchronized through antenna coupling

Top array: 4x4 Gunn diode array
- 9.6 GHz operation
- 22 Watts ERP
- 1% DC-to-RF efficiency

Bottom array: 4x4 MESFET array
- 8.2 GHz operation
- 10 Watts ERP
- 26% DC-to-RF efficiency

Proof of concept arrays, led to better understanding of coupled-oscillator systems including mutual synchronization, phase dynamics, beam-scanning, and mode-locking





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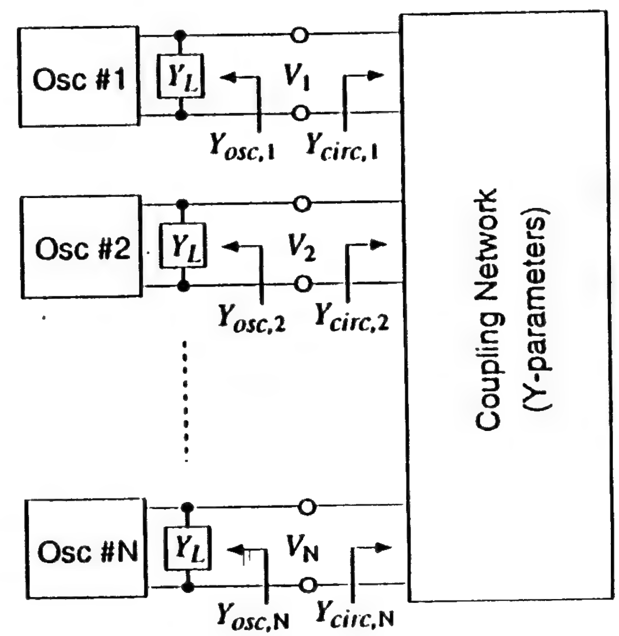
Arbitrary Coupling Network

Enforce node coditions:

$$Y_{\mathrm{osc},i}(\omega, V_i) + Y_{\mathrm{circ},i}(\omega, \overline{V}) = 0$$

$$i = 1, 2, \ldots N$$



Convert to dynamic equations (Kurokawa):

$$\omega \Rightarrow \left[\omega_i + \frac{d\phi_i}{dt} - \jmath \frac{1}{A_i}\frac{dA_i}{dt}\right]$$

Define coupling parameters: $\kappa_{ij} \equiv Y_{ij}/G_L$

Broadband condition:

$$\frac{\omega_i}{2Q}\sum_{j=1}^{N} \frac{\partial \kappa_{ij}}{\partial \omega}\frac{A_j}{A_i} \ll 1$$

Leads to: $\longrightarrow$

$$\frac{dA_i}{dt} = \frac{\mu\omega_i}{2Q} S_i(A_i)A_i - \frac{\omega_i}{2Q}\sum_{j=1}^{N} A_j \,\mathrm{Re}\left\{\kappa_{ij} e^{\jmath(\theta_j - \theta_i)}\right\}$$

$$\frac{d\theta_i}{dt} = \omega_i - \frac{\omega_i}{2Q}\sum_{j=1}^{N} \mathrm{Im}\left\{\kappa_{ij}\frac{A_j}{A_i} e^{\jmath(\theta_j - \theta_i)}\right\}$$

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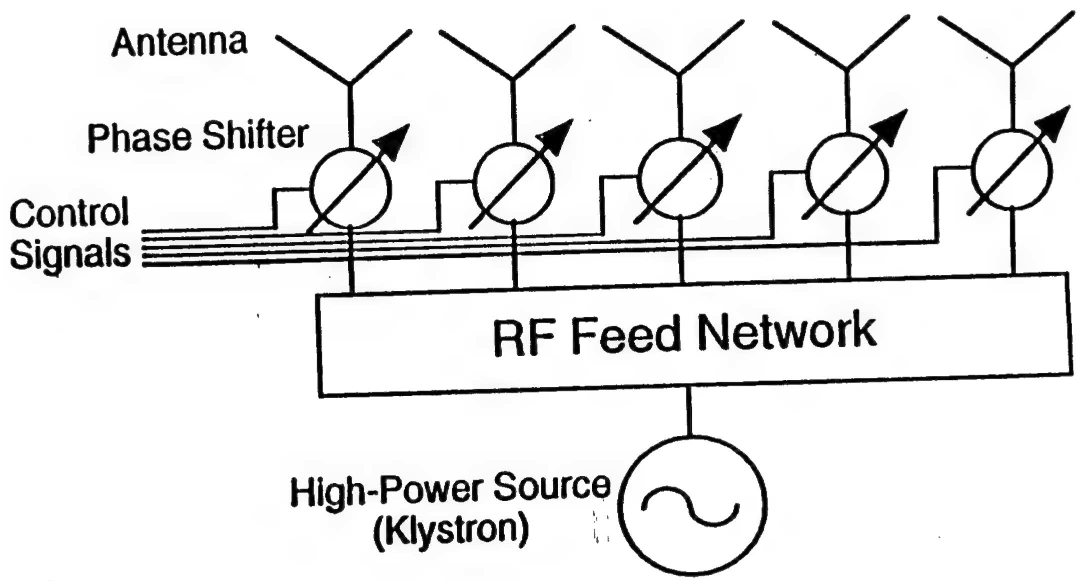
New Beam-Scanning Method

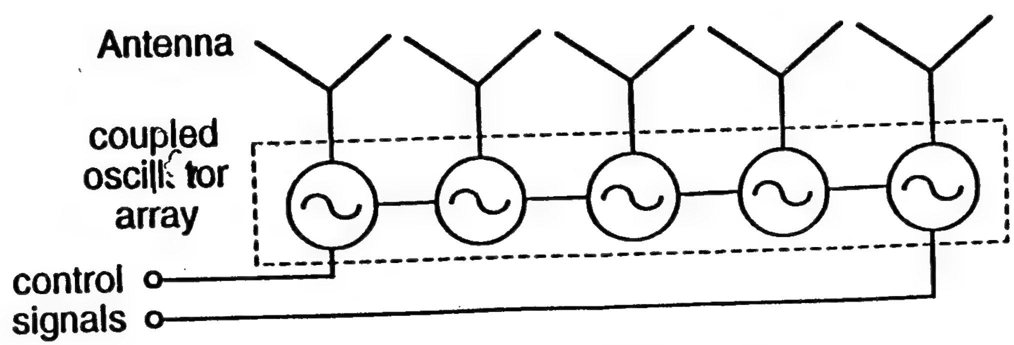
Conventional:

- Difficult, expensive to make
- Low-yield fabrication
- Requires high-power source
- Tough to monolithically integrate entire system



Coupled-Oscillator Arrays:

- No phase shifters !!
- Only two controls lines for scanning
- Distributed solid-state source: no feed network
- Ideal for low-cost, hand-held or mobile applications



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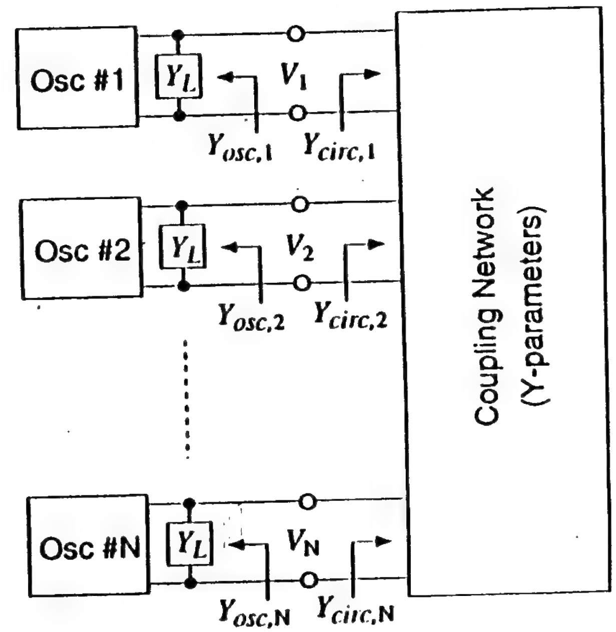
Arbitrary Coupling Network



Enforce node coditions:

$$Y_{\mathrm{osc},i}(\omega, V_i) + Y_{\mathrm{circ},i}(\omega, \overline{V}) = 0$$
$$i = 1, 2, \ldots N$$

Convert to dynamic equations (Kurokawa):

$$\omega \Rightarrow \left[\omega_i + \frac{d\phi_i}{dt} - \jmath \frac{1}{A_i}\frac{dA_i}{dt}\right]$$

Define coupling parameters: $\kappa_{ij} \equiv Y_{ij}/G_L$

Broadband condition:

$$\frac{\omega_i}{2Q}\sum_{j=1}^{N} \frac{\partial \kappa_{ij}}{\partial \omega}\frac{A_j}{A_i} \ll 1$$

Leads to: ⟶

$$\frac{dA_i}{dt} = \frac{\mu\omega_i}{2Q}S_i(A_i)A_i - \frac{\omega_i}{2Q}\sum_{j=1}^{N} A_j \,\mathrm{Re}\left\{\kappa_{ij} e^{\jmath(\theta_j - \theta_i)}\right\}$$

$$\frac{d\theta_i}{dt} = \omega_i - \frac{\omega_i}{2Q}\sum_{j=1}^{N} \mathrm{Im}\left\{\kappa_{ij}\frac{A_j}{A_i} e^{\jmath(\theta_j - \theta_i)}\right\}$$

Tightly Coupled Patch/Oscillator Arrays

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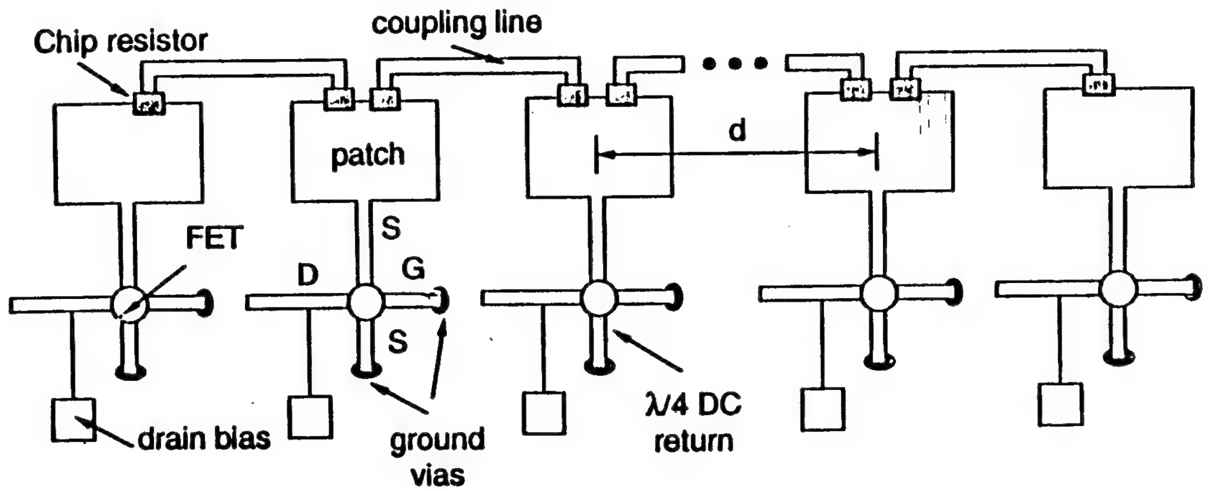
- Strongly-coupled array
- broadband coupling network
- fabricated on er=10.8 substrate
- 4GHz, d=0.3 λ_0
- Optimum power/efficiency design: 43% Class AB



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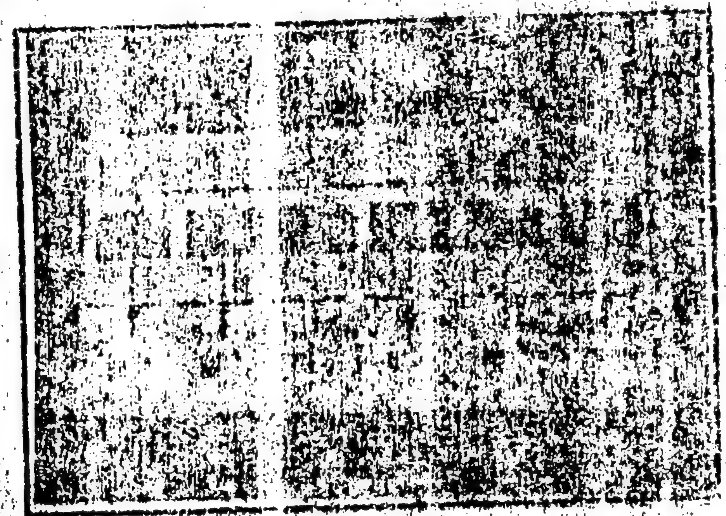
Scanning Measurements

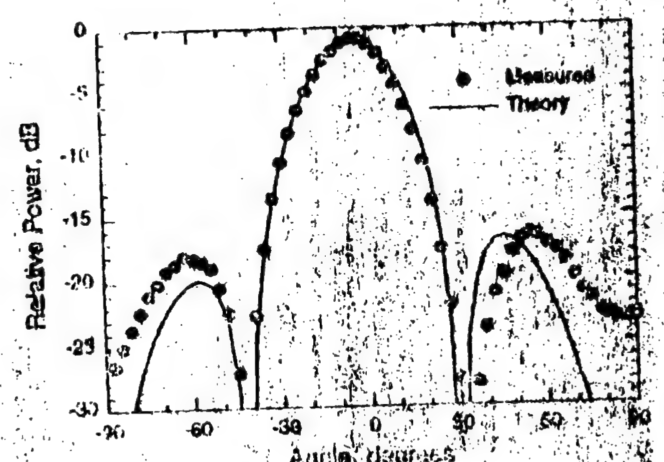
6 x 1 MESFET Array Prototype with patch antennas

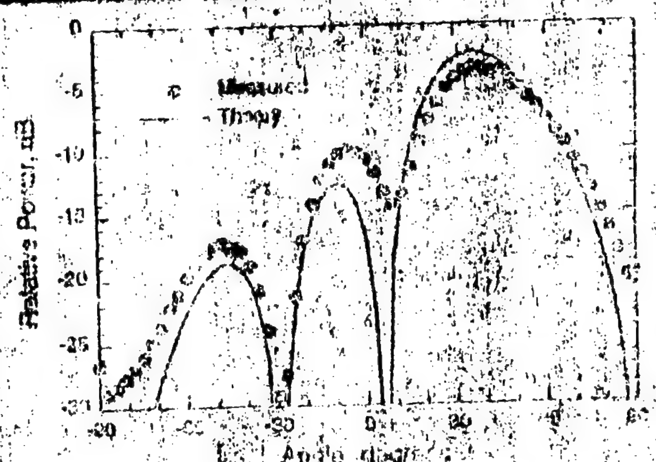
4GHz optimum efficiency oscillator design **(43% DC-to-RF conversion)**

Results:
- **Continuous scanning from -40° to +40° off broadside**
- accomplished by adjusting end-element frequencies (drain bias)

Excellent correlation with theory







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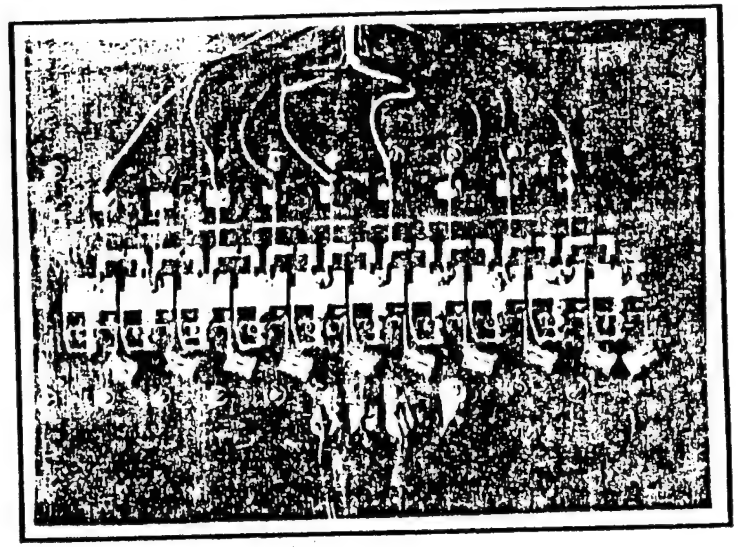
Linear VCO Array

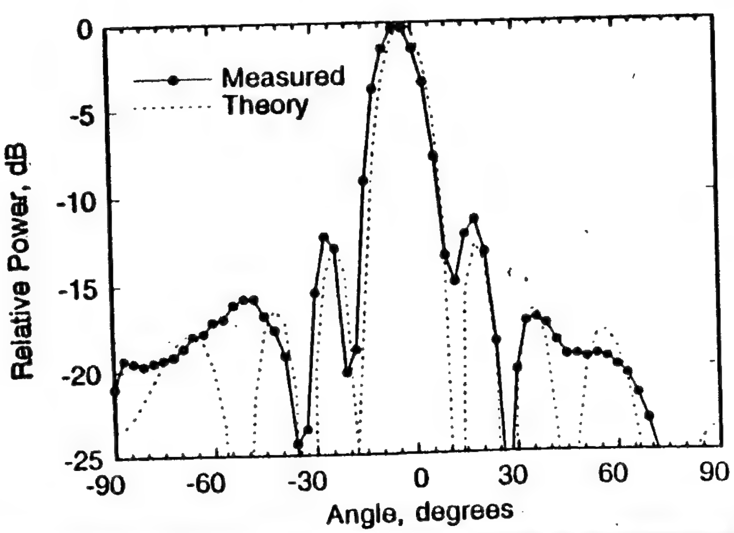
8 x 1 MESFET VCO Array Prototype
Varactor-tuned patch antennas

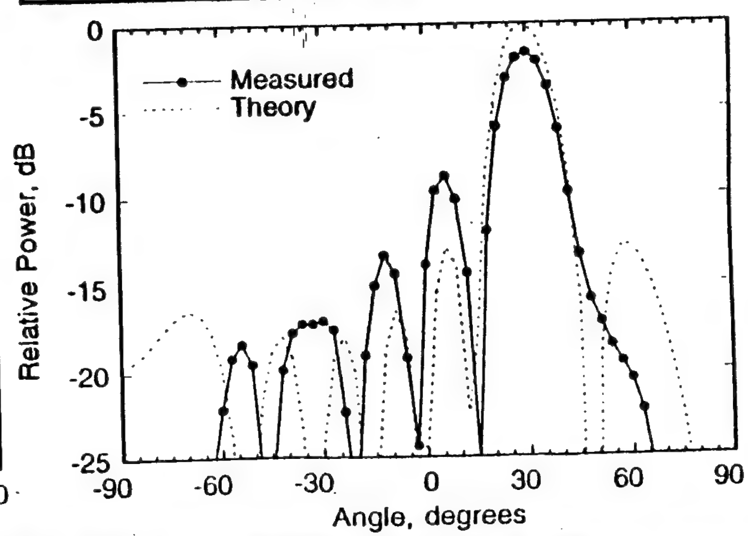
1 Watt output at 8.4 GHz
(10 Watt Effective Radiated Power)

Results:
- Simpler operation due to VCO, possibility of computer control
- **Continuous scanning from -15° to +30° off broadside**

Excellent correlation with theory







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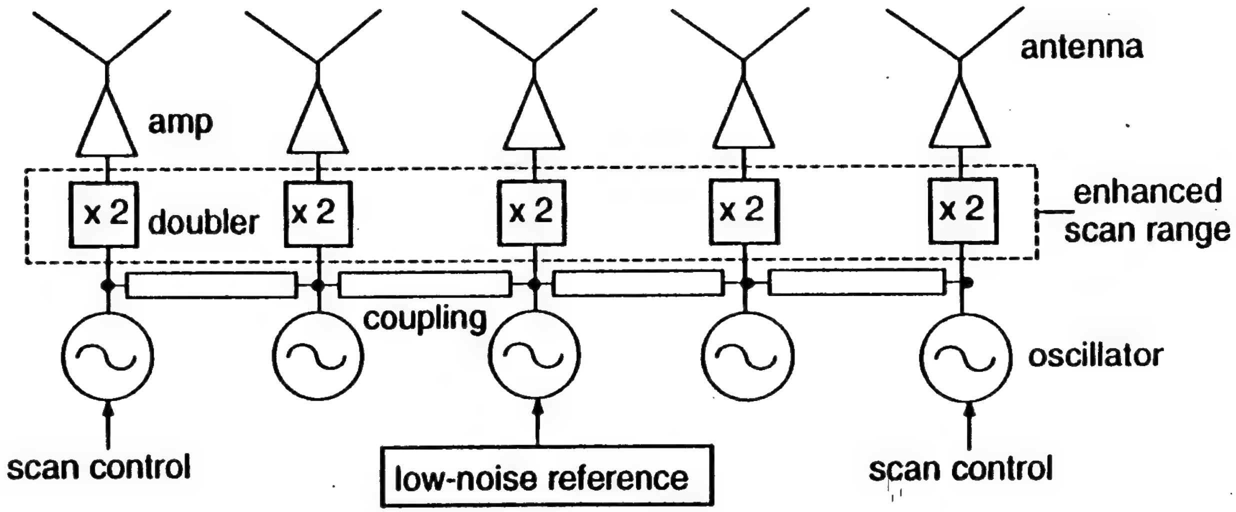
Improved Scanning Oscillator System



- doubled output greatly increases scan range: doubles inter-element phase shift for a given tuning. Theoretically full hemispherical coverage.
- doublers simplify oscillator design for given output frequency
- amplifier array for best efficiency, also simplifies oscillator design
- low phase noise by locking to stable reference

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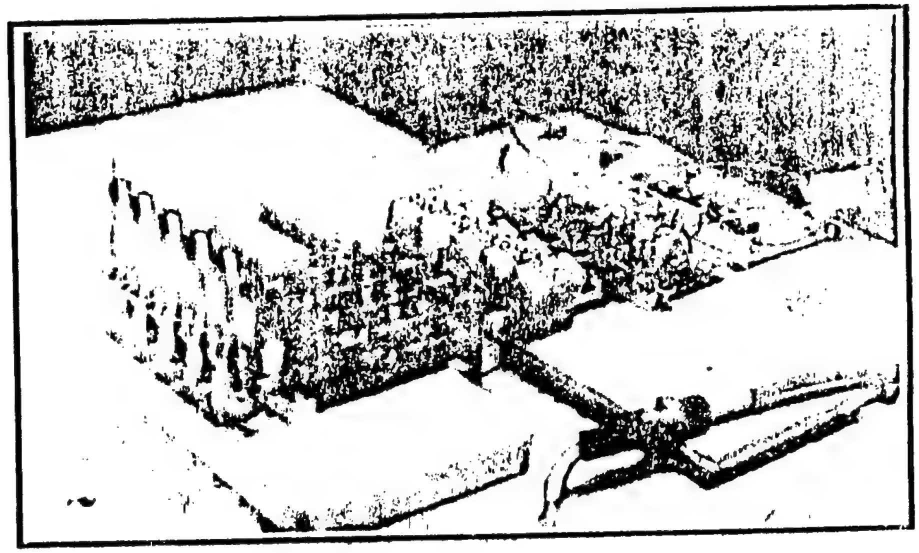
Enhanced Scan Angle

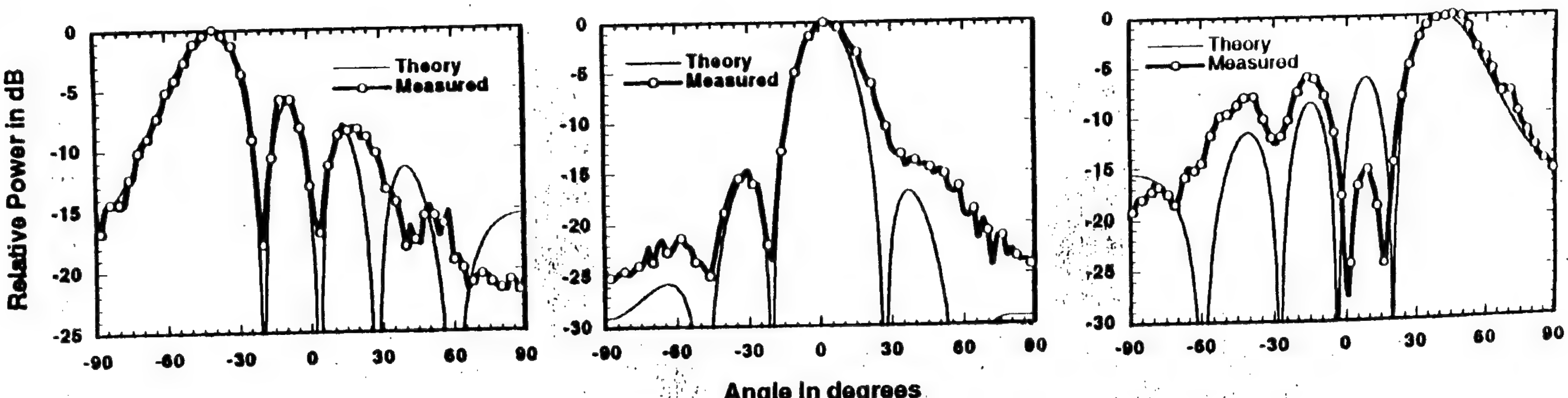


Array

- MESFET/PATCH oscillator array operating at 4GHz doubled to 8GHz
- $\lambda/2$ antenna spacing at 8GHz

Measured Results

- Beam was steered from -40° to +40° through VCO tuning
- Maximum inter-element phase shift attained (after frequency doubling) is +/-133°



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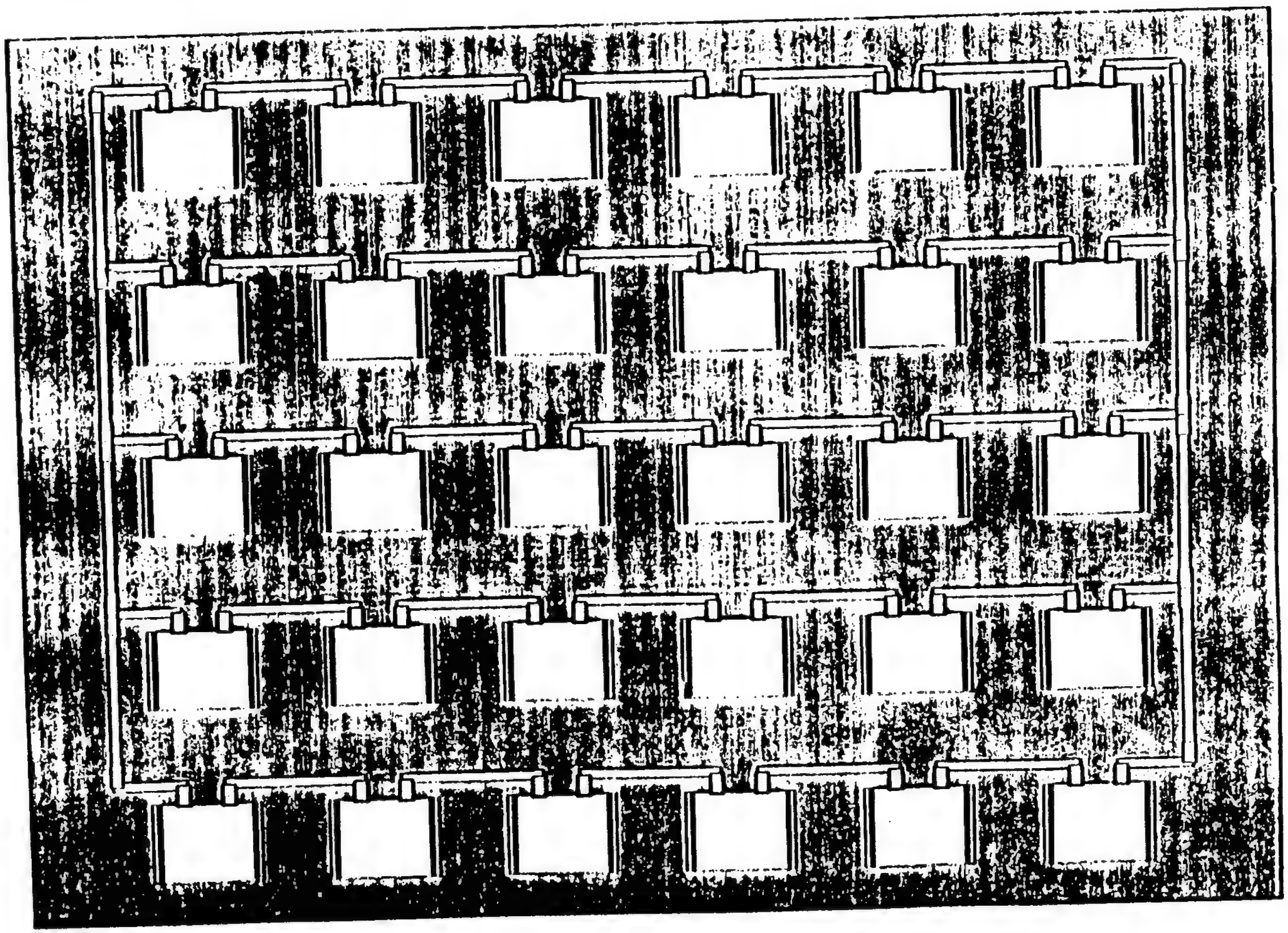
Coupling 2D Oscillator Arrays

Couple rows together vertically at edge elements



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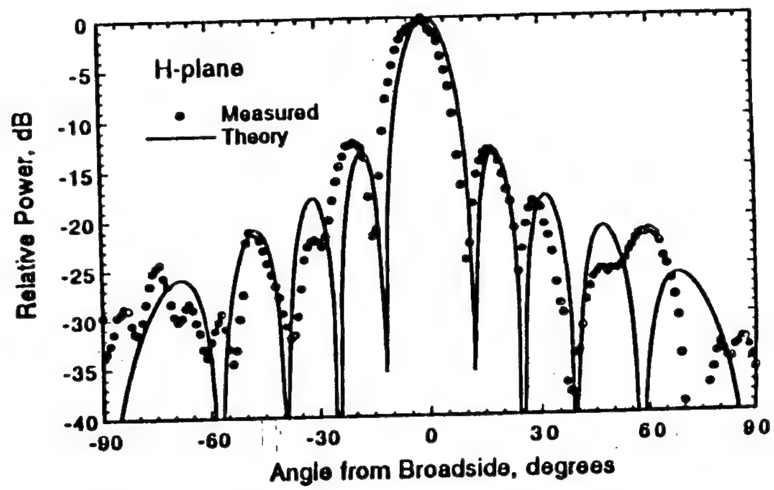
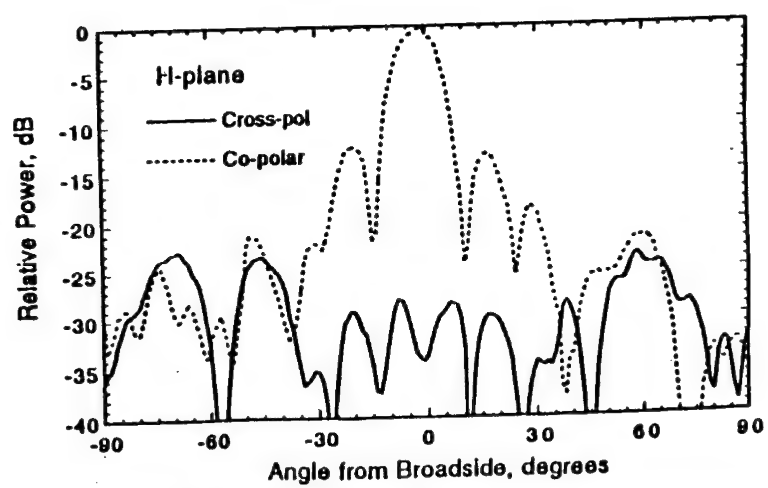
Results for 6 x 2 array

1.7 kW for 6x3 array

- 933 Watt Effective Radiated Power (EIRP)
- Estimated directivity of 81 (19 dB) from pattern measurements (theory predicts 64)
- Leads to total radiated power = **11.7 Watts** 1 W/element
- Array draws 9 Amp @ 8.5 V = **15% efficiency** (wall plug) (includes all bias circuitry)
- Axial ratio <-25dB within HPBW →





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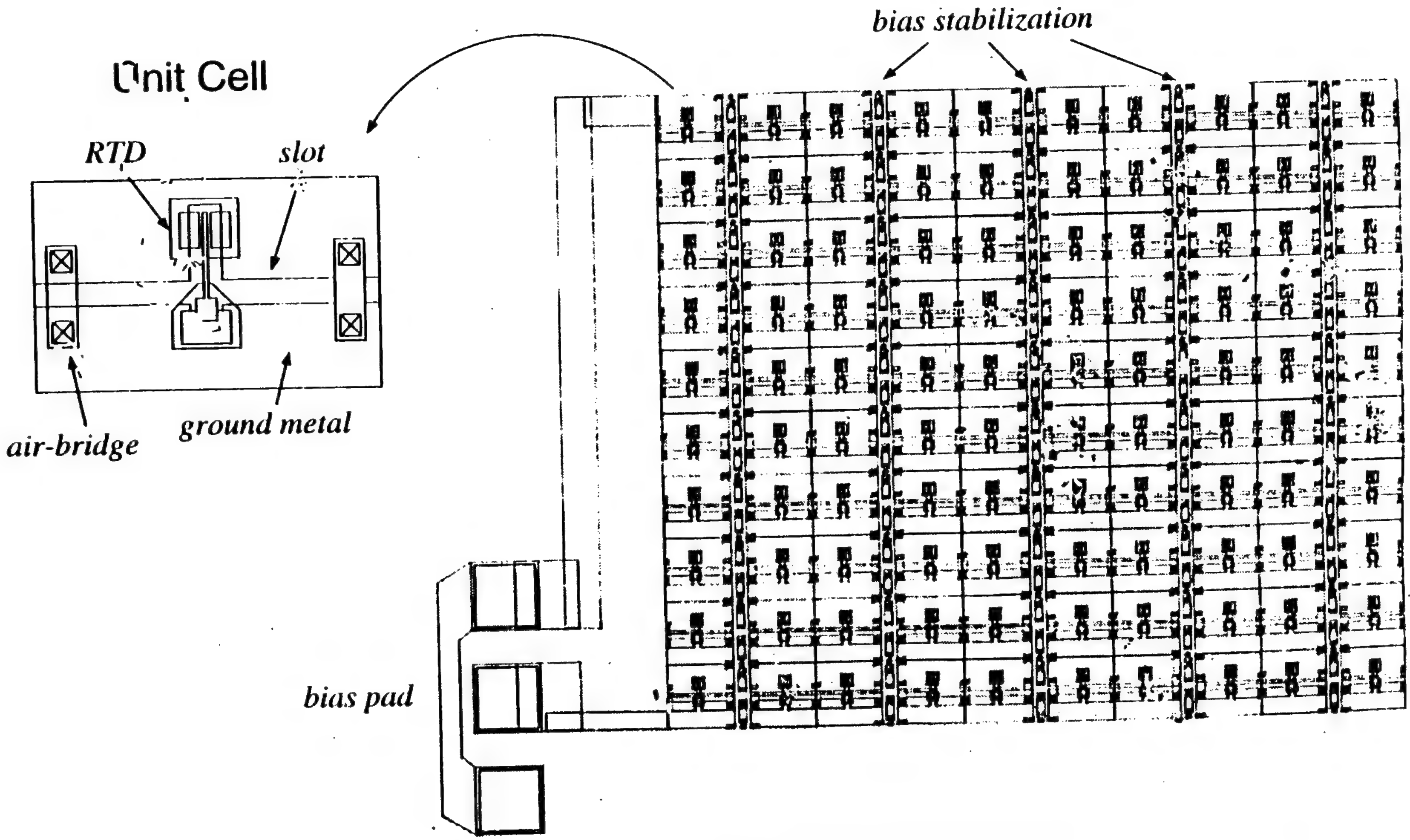
300GHz Schottky-Contact RTD Array



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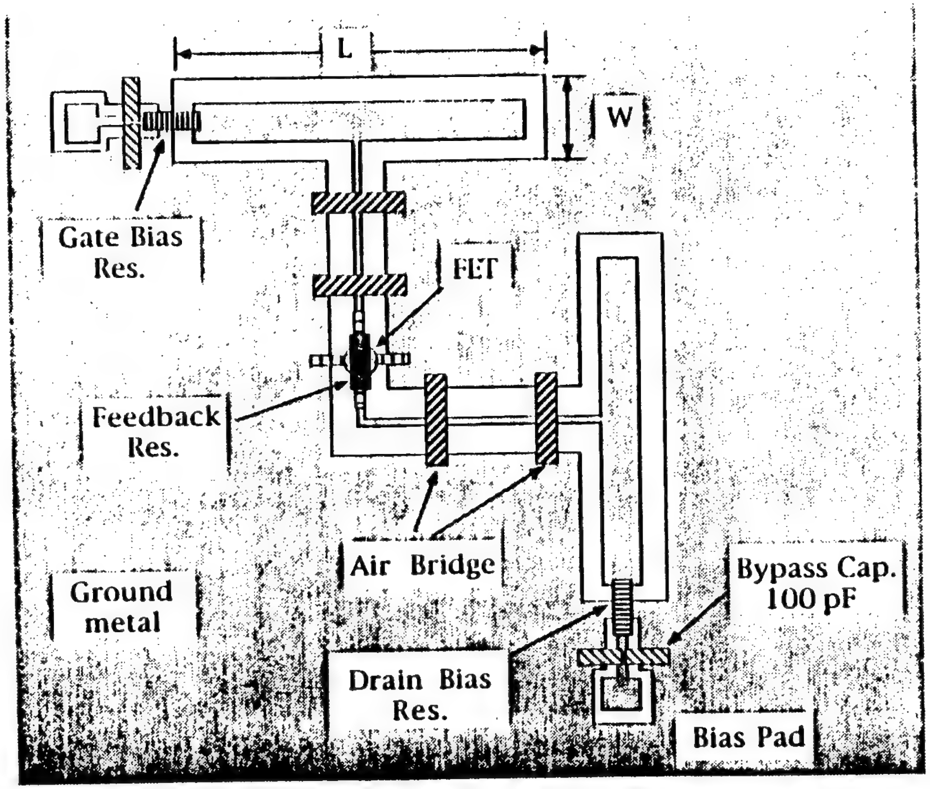
Circuit Layout of Planar Amplifier Array Using Folded-Slot Antennas



- The bandwidth is wider because the extra slot tends to cancel the off resonace reactance of a single slot.
- Broadband (DC - 4GHz) resistively feedback amplifier design.

  GaAs MESFET, NE32184A

  $Z_{in} = Z_{out} = 125\Omega$

  8dB gain @ 4GHz
- Input impedance of folded-slot antenna is estimated from Babinet's principle.

  $Z_{folded-slot} \approx 125\Omega$

Folded-slot antennas are attractive for active arrays because they are simple to make (one mask step) and can be easily integrated with three-terminal devices (HEMT and HBT).

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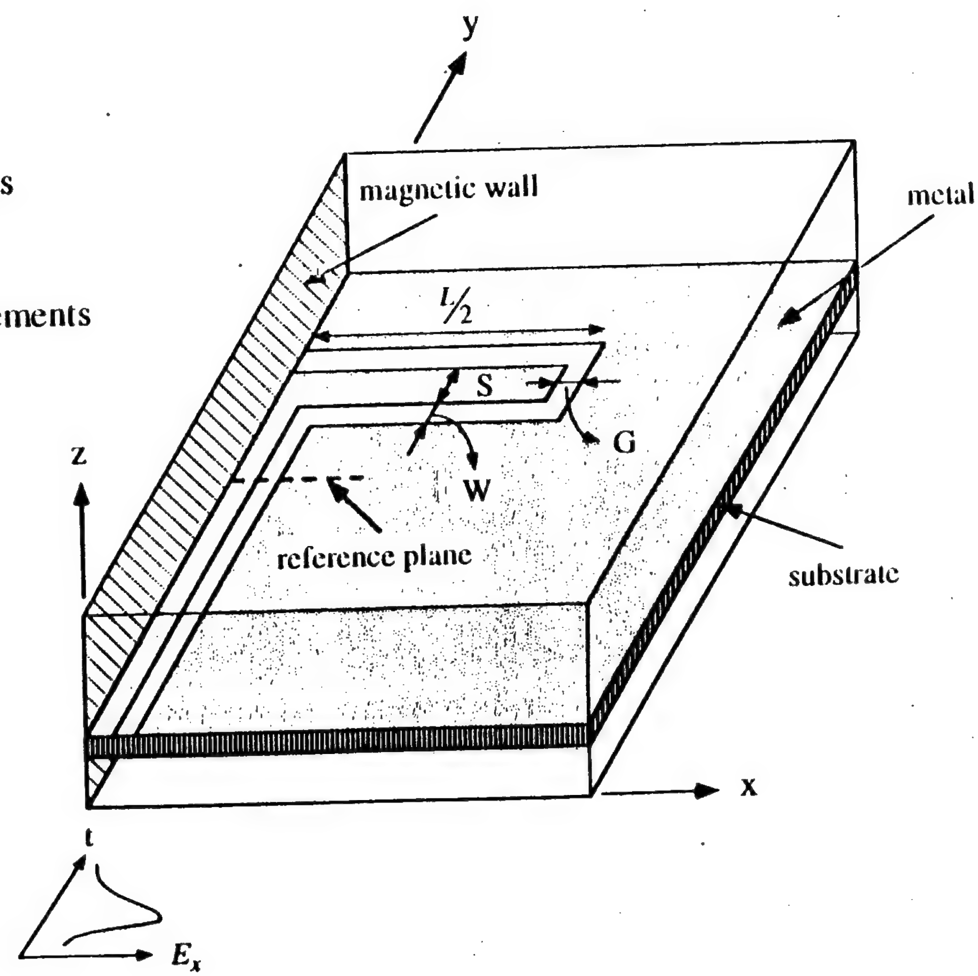
Finite-Difference Time-Domain (FDTD) Method

Why FDTD technique ?

- Flexibility --- suitable for various circuit configurations.
- Active and nonlinear lumped elements can be included.
- Easy programming.



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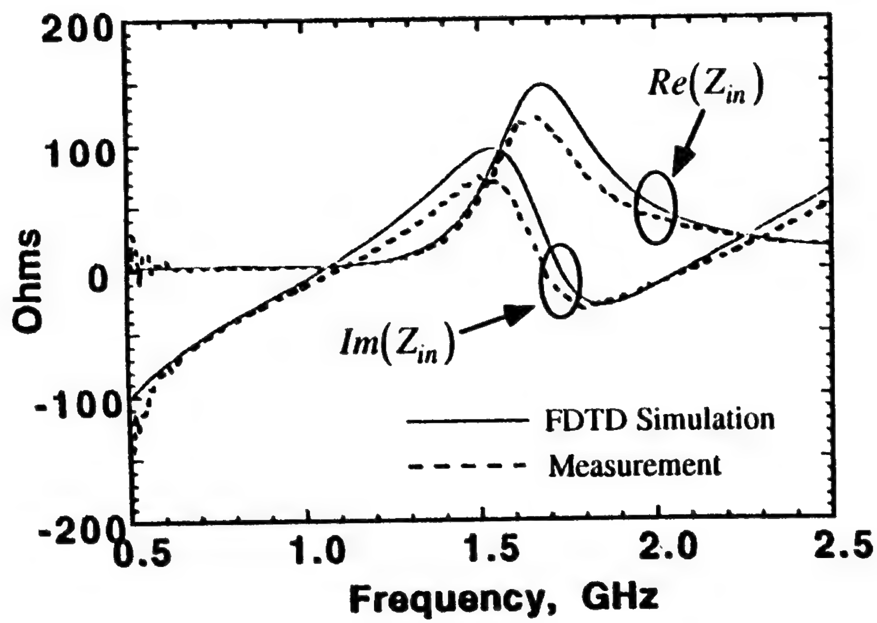
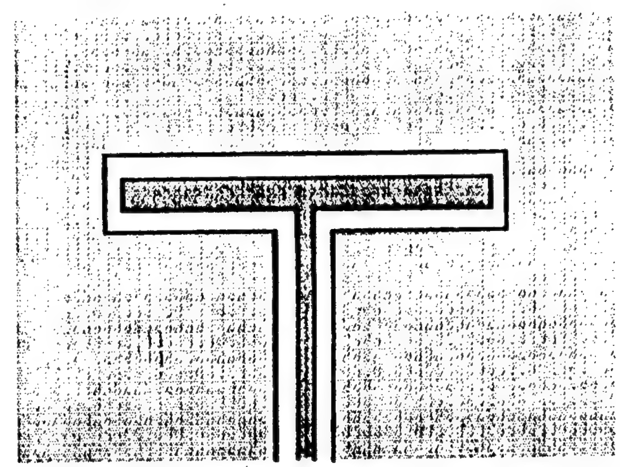
Comparison Between Measurement and FDTD Simulation Results



Thickness = 0.787mm $\varepsilon_r = 2.2$



- Excellent agreement between simulation and measurement.
- Great flexibility of analyzing different circuit configurations.

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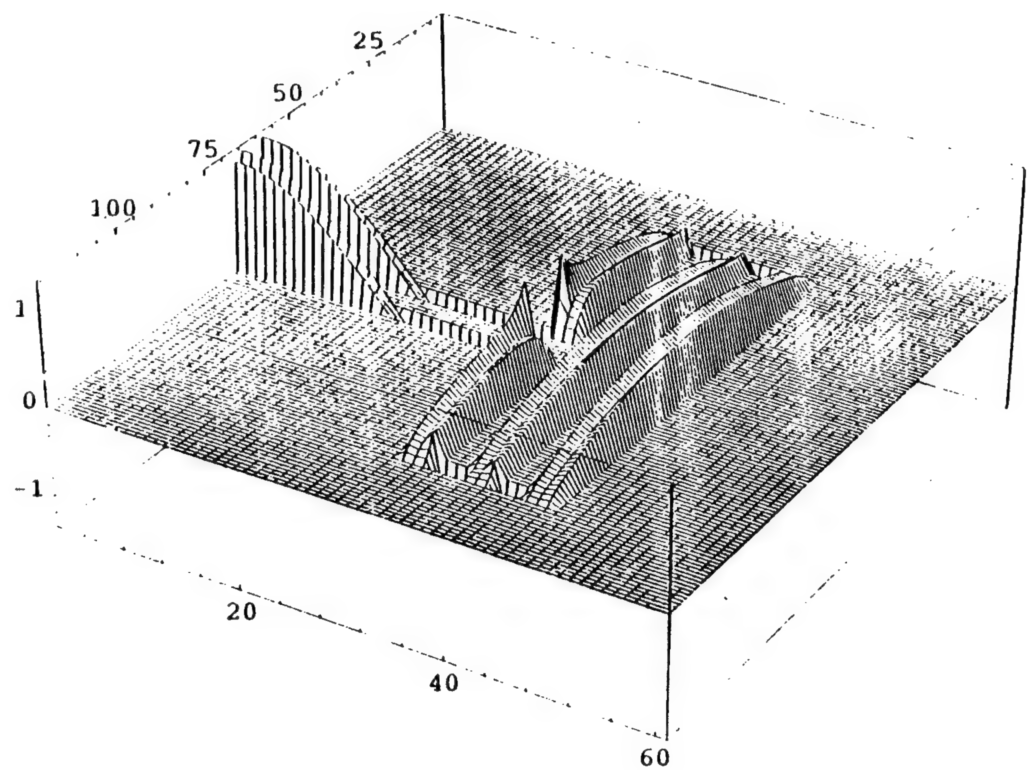
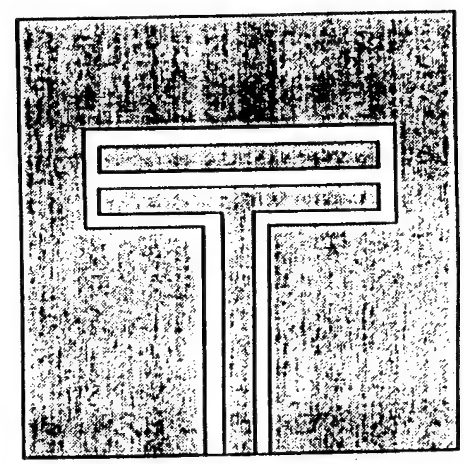
Steady State Field Distributions in the Triple Folded Slot Antenna



Plan view of the antenna



- Fields in three slots are in phase as expected.
- FDTD is a great visual tool for electromagnetic problems.

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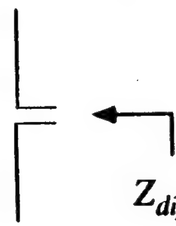
Impedance Scaling using Multiple Slots

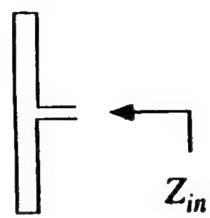
Dipole

Half-wave dipole :



$Z_{dipole} \approx 70\Omega$

Folded dipole :



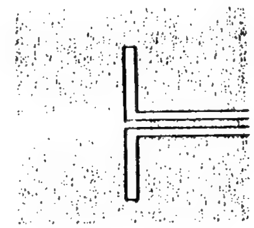
$Z_{in} = 4Z_{dipole} \approx 300\Omega$

N-element folded dipole :

$$Z_{in} = N^2 Z_{dipole}$$

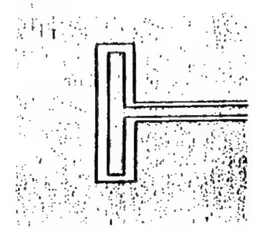
Slot

Half-wave single slot :



$Z_{slot} \approx 500\Omega$

Folded slot :



$Z_{in} = Z_{slot}/4$

N-element folded slot :

$$Z_{in} = Z_{slot}/N^2$$

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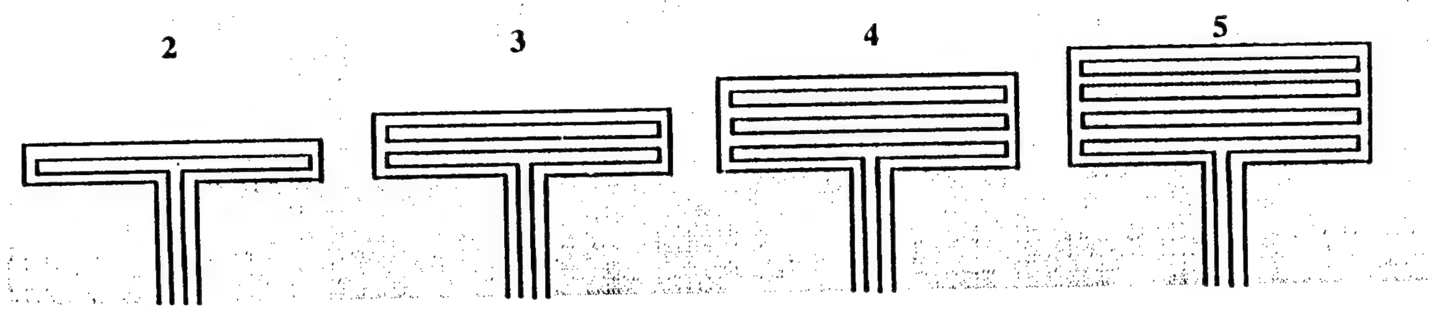
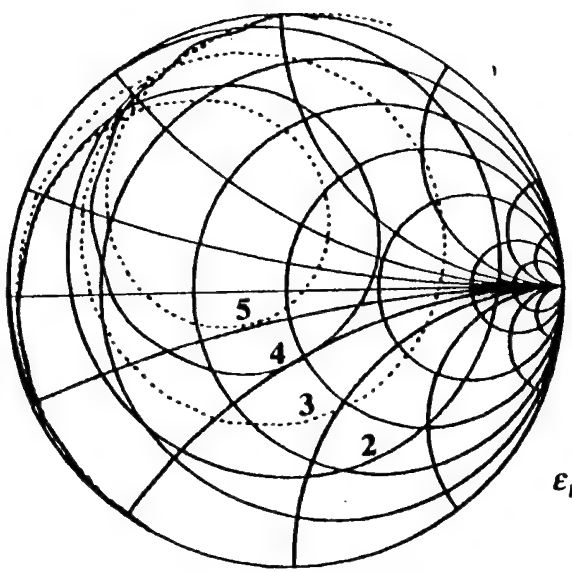
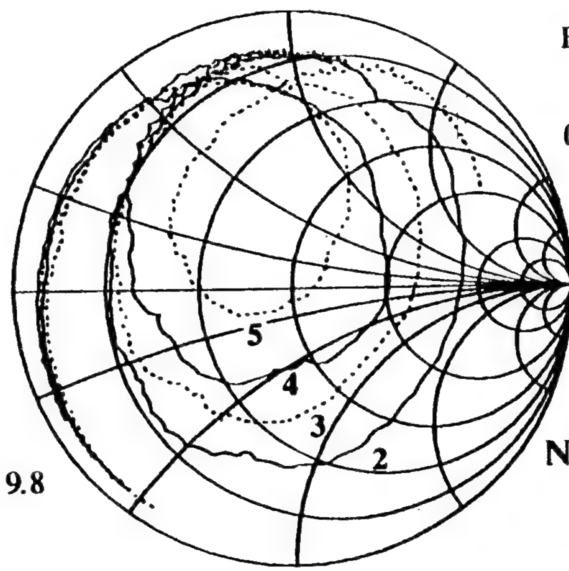
Impedance Scaling Using Multiple-Slot Antennas





FDTD simulation

$\varepsilon_r = 9.8$



Measurement

Frequency Range :
5 GHz to 15 GHz
0.635 mm Alumina substrate

Notes :

The resonant frequencies of these four antennas are about the same.

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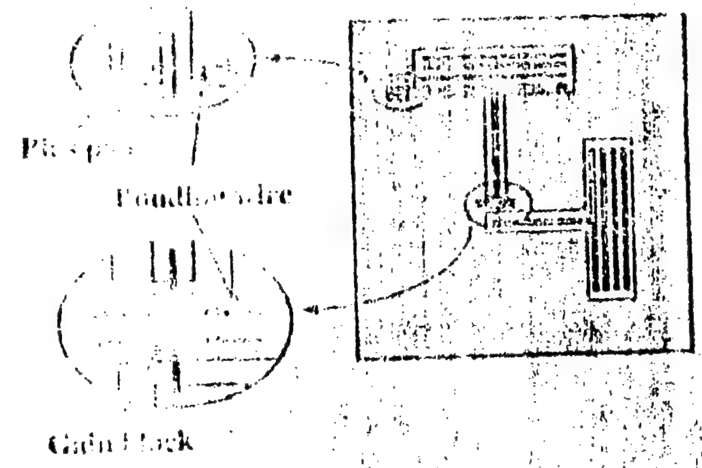
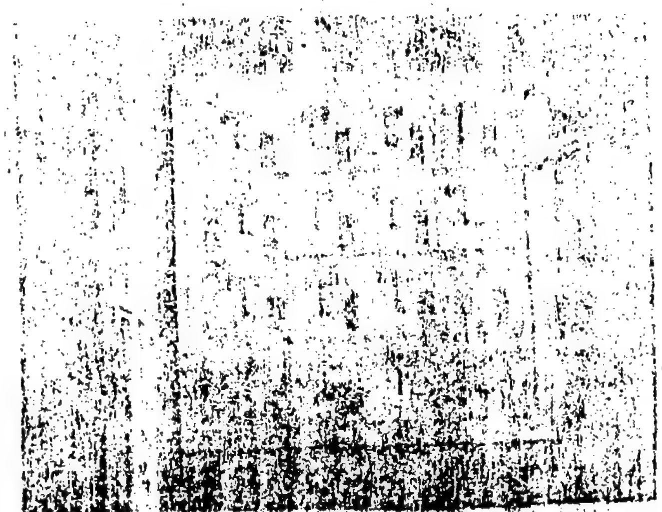
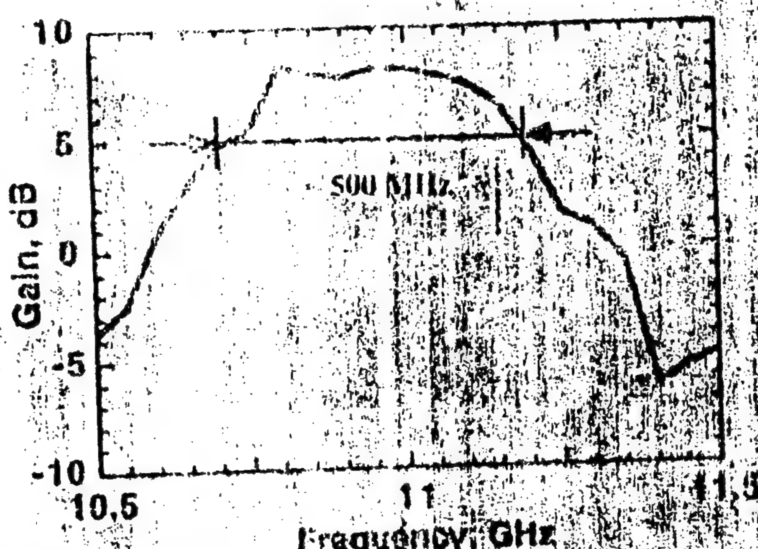
UC SB

4 x 4 HBT Amplifier Array





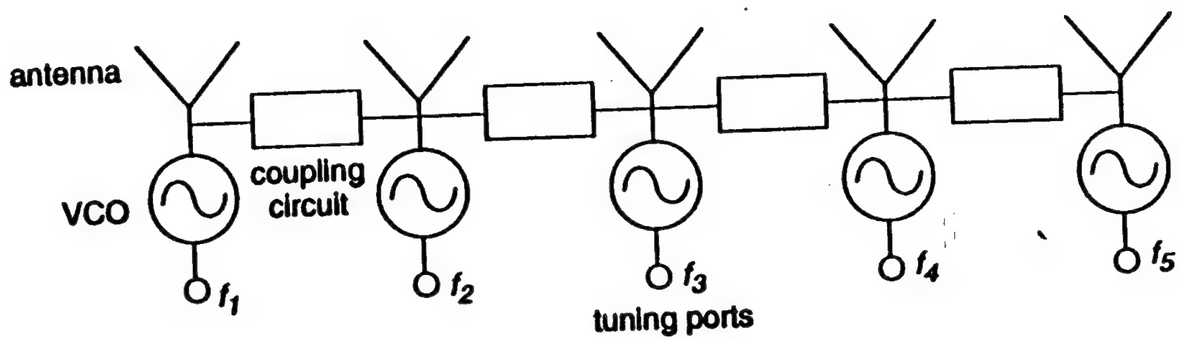


- 4x4 HBT array @ 10 GHz
- 0.635 mm Alumina substrate
- 50 Ω five-slot antennas, no matching
- 8 dB gain with ≈ 5 % bandwidth

UCSB
University of California, Santa Barbara

Bilateral Injection-Locking Approach

"Mutual Synchronization"
"Inter-Injection-Locking"



Oscillators coupled through some electromagnetic coupling circuit:

- mutual coupling between antennas
- cavity coupling
- transmission-lines circuits

Plane Wave Amplifier Chip
Version Using Folded Slot Antenna

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Rockwell
Science Center

SCP.0938A.090595

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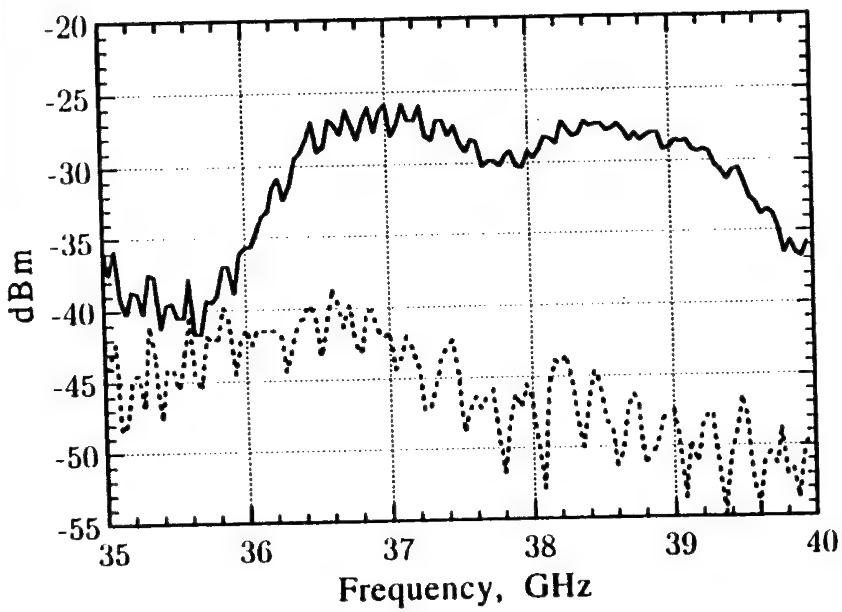
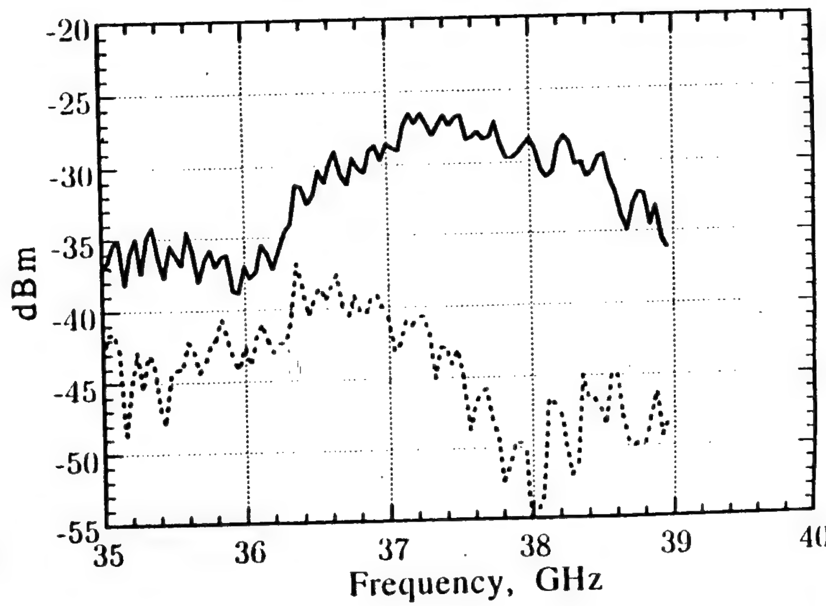
UCSB University of California, Santa Barbara

Preliminary Measured Results of the Amplifier Array

2 x 5 Array

Bias conditions : $V_{be} = 1.5V$, $I_b = 2mA$
$V_{ce} = 3V$, $I_c = 30mA$





——— Bias on - - - - - Bias off

- **The on/off ratio is greater than 15dB from 37GHz to 40GHz.**
- **The 3dB bandwidth is close to 3GHz.**

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What has limited our progress

low power, packaged devices
(limited performance)

lack of access to monolithic fab

scope of problems addressed, frequencies

→ no "kick-ass" result yet
∴ limited funding & global interest

Some directions

- amplifier arrays – natural place for industrial involvement, 6.1 → 6.2 or 6.3
- stronger interaction between systems-device-circuit people
- better guidance from Gov't/industry as to potential applications/frequency ranges
- Universities continue doing "new" things

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QO Technology Survival Path

- Based on the opinion of several experts, a realistic challenge for quasi-optical technology is a proof-of-principle power amplifier module that would provide an evidence of high power amplifications at millimeter-wave frequencies. Such a demonstration may ensure a suitable market place for this emerging technology, perhaps at first as a replacement for high volume conventional "fixed phase" power source, such as TWTs used in Ka and W-band missile seeker systems.
- Prior to building a huge infrastructure for QO technology, perhaps it is ideal for ARPA to support a single QO industrial program (~2 years) for establishing a proof-of-principle for QO technology. Under such a program, the QO Technology Survival would be depend on its demonstrated merits.
- Compact's QO Mission:
  - Develop a set of *commercially available* modeling and analysis tools to support the design and development of quasi-optical systems.
  - Through our " QO CAD alliance members", we possess a significant source of uncommercialized quasi-optical CAD tools and techniques. This will enable us to develop cost effective CAD products through "shared development and resources".

COMPACT SOFTWARE

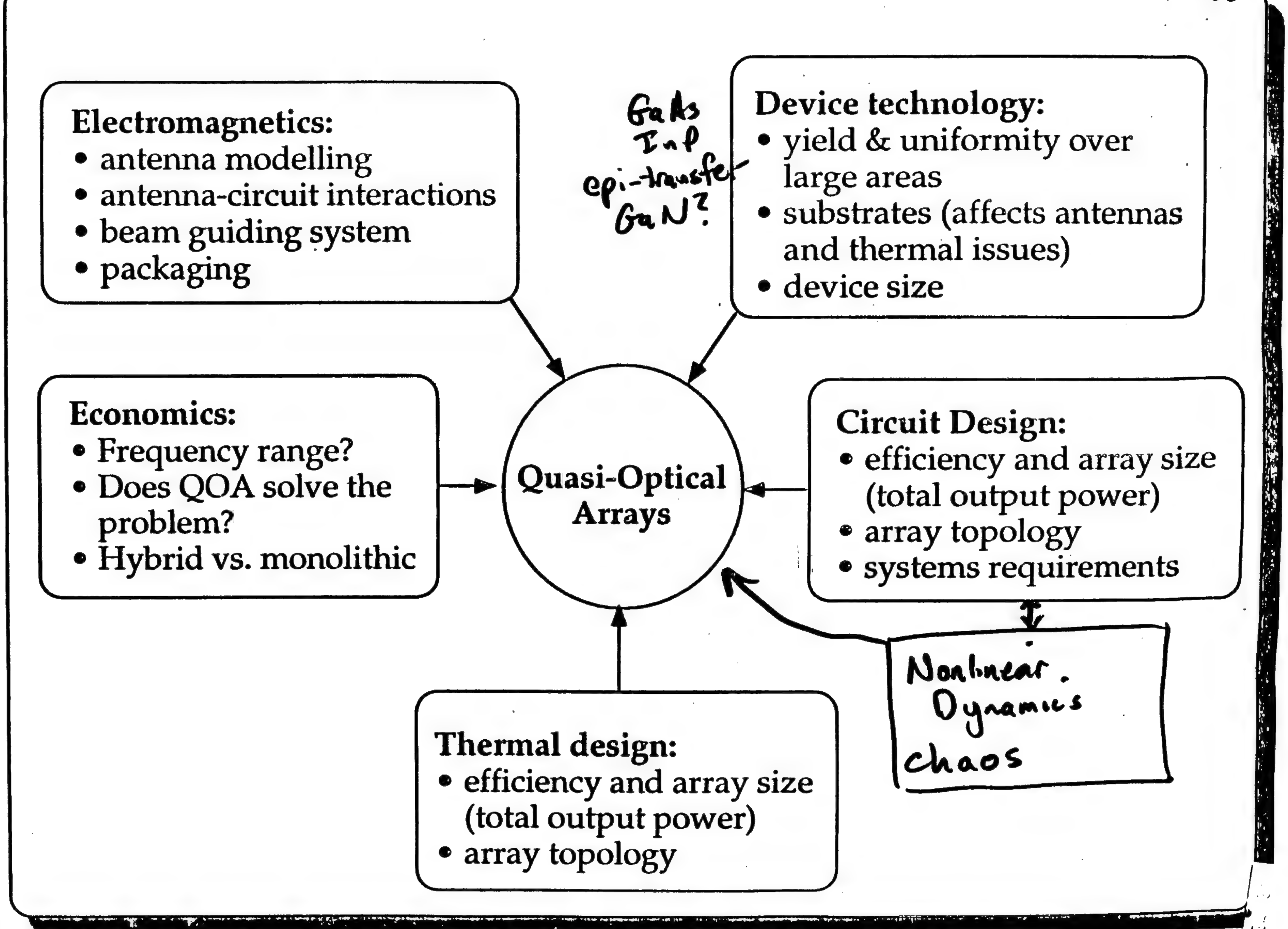
rayork@ece.ucsb.edu

UC SANTA BARBARA

- coupled oscillator systems & modelling
- Novel scanning concepts
- integrated antenna design
- antennas for arrays
- modelling of arrays & grids using FDTD
- amplifier arrays
- Quasi-optical distributed circuits

conventional antennas vs. grids

supported by ARO, NSF, Rockwell Science Center, Hughes Research Laboratories, Jet Propulsion Lab


Electromagnetics:
• antenna modelling
• antenna-circuit interactions
• beam guiding system
• packaging
GaAs
InP
epi-transfer
GaN?
Device technology:
• yield & uniformity over large areas
• substrates (affects antennas and thermal issues)
• device size
Economics:
• Frequency range?
• Does QOA solve the problem?
• Hybrid vs. monolithic
Quasi-Optical Arrays
Circuit Design:
• efficiency and array size (total output power)
• array topology
• systems requirements
Nonlinear.
Dynamics
chaos
Thermal design:
• efficiency and array size (total output power)
• array topology

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Quasi-Optical Research

at the University of Colorado

Zoya Popović

Associate Proffessor, Electrical Engineering
UNIVERSITY OF COLORADO, BOULDER

Students:

Scott Bundy·
Tom Mader·
Jon Schoenberg·
Wayne Shiroma
Milica Markovic
Jon Dixon
Stein Hollung
Eric Bryerton
Michael Forman
Joe Tustin
Robert Brown

· now with SCT, Inc., Golden, CO
· now with Hughes, El Segundo
· now with Phillips Airforce Labs, Albaquerque

Funding:

NSF
ARO
Lockheed Martin
Compact Soft.(Air Force)
Compact Soft.(ARPA)
NAWC, China Lake
CAMI, ETAP
MURI (U of M)
SCT (Air Force)

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Recent advances in quasi-optics at the University of Colorado 1994 and 1995, *Zoya Popović*

Amplifiers:

- 24-element patch lens amplifier transmitter, 9 dB absolute power gain, 10 GHz.
- 24-PHEMT lens amplifier receiver with 2-stage LNAs, 13 dB gain, 1.9 dB noise figure, 30 dB isolation, 10 GHz.
- 4-MESFET high-efficiency power amplifier array, 2.4 W at 5 GHz, 74% drain eff., 64% PAE, 84% power-combining eff.
- Design of 2-Watt Ka-band array (with Lockheed Martin, Orlando).
- Monolithic 60-GHz HEMT array (with Lockheed Martin, Baltimore).
- Multistage lens amplifiers, X-band.

Oscillators and mixers:

- Three-dimensional grid oscillators, 100 HEMTs in 4 grids at 5 GHz.
- Dual-frequency grid oscillator using an electronically tunable frequency selective surface, 4 and 6 GHz.
- Design of 36-MESFET Ka-band high power hybrid oscillator (with NAWC, China Lake).
- Design of monolithic 100-HEMT Ka-band oscillator (with TLC, SBIR I and Honeywell).
- Grid oscillators as self-oscillating mixers, 5 and 10 GHz, 100-800 MHz IF.

Other components:

- Linear-to-circular polarizer, X-band, 1.1 dB loss, 1.2 dB axial ratio.
- Isolator, X-band, -19 and 9 dB isolation for the V and H components.
- Digital phase modulators, X-band, 0-90 and 0-180 deg in transmission.
- Electronically-tunable partially transparent reflector (FSS), 30% tuning, transmission 0.1 to 1 from 2 to 10 GHz.

Subsystems:

- Two-stage power combining with 28-HEMT grid oscillator feeding a 24-HEMT lens amplifier, X-band.
- Beam steering, beam forming and beam switching with lens amplifier.
- Receiver with lens amplifier and grid subharmonic self-oscillating mixer, C-X band.
- Angular diversity with a receiving lens amplifier, X-band, -30 to 30 deg.

Quasi-Optical Amplifier Feed Techniques

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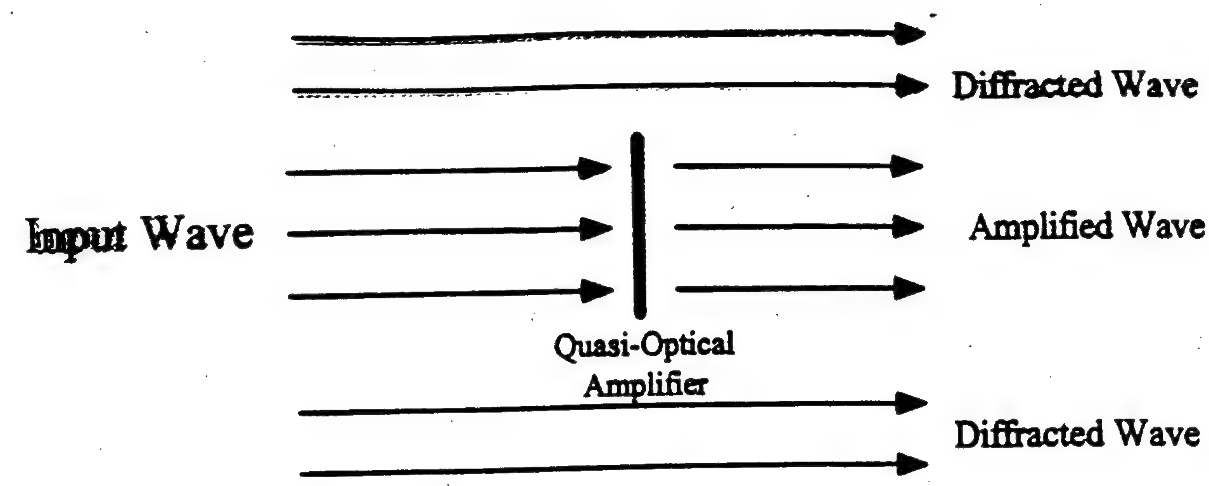

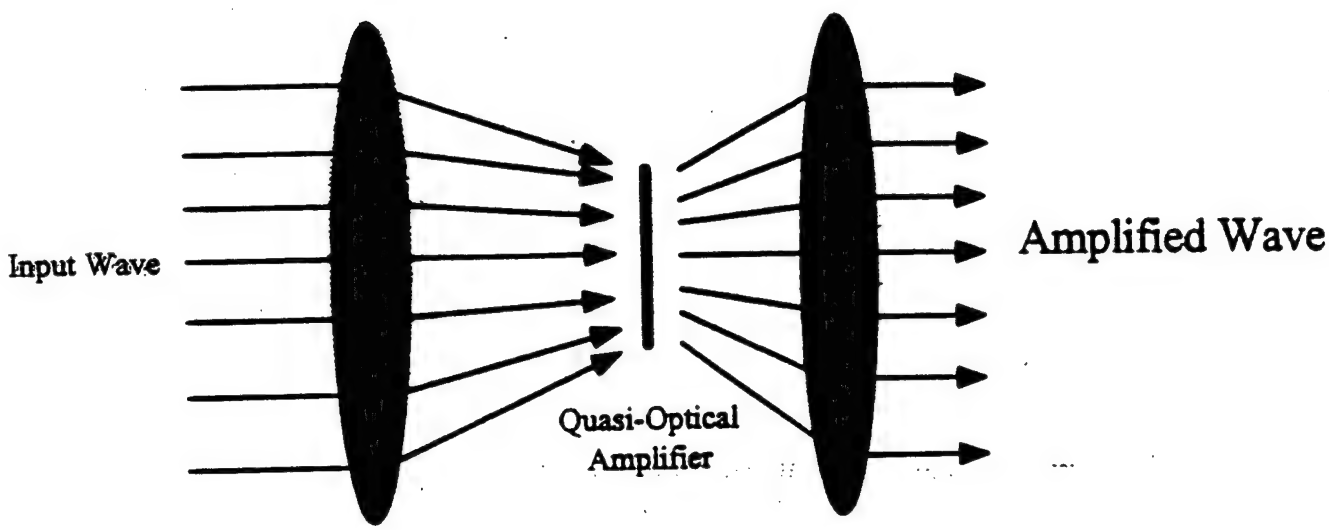

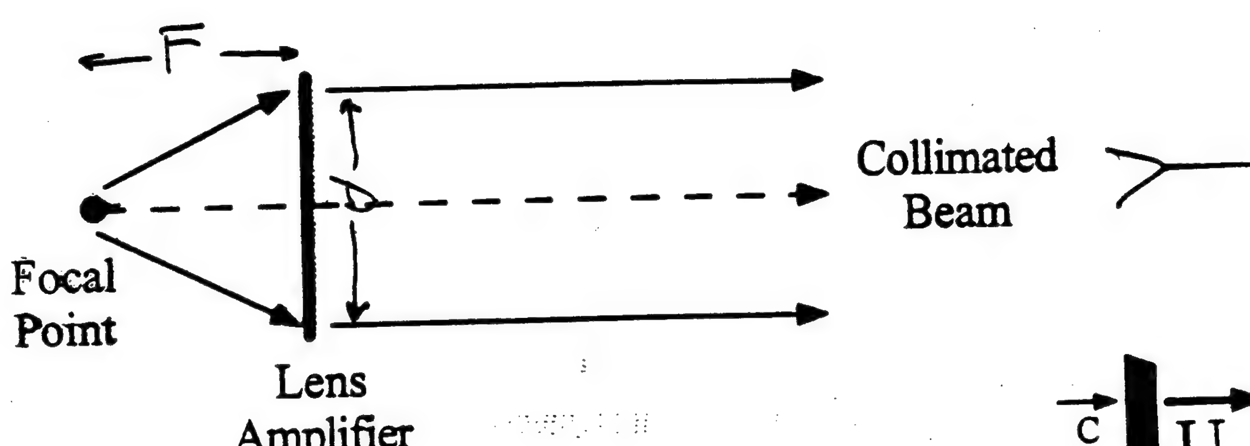

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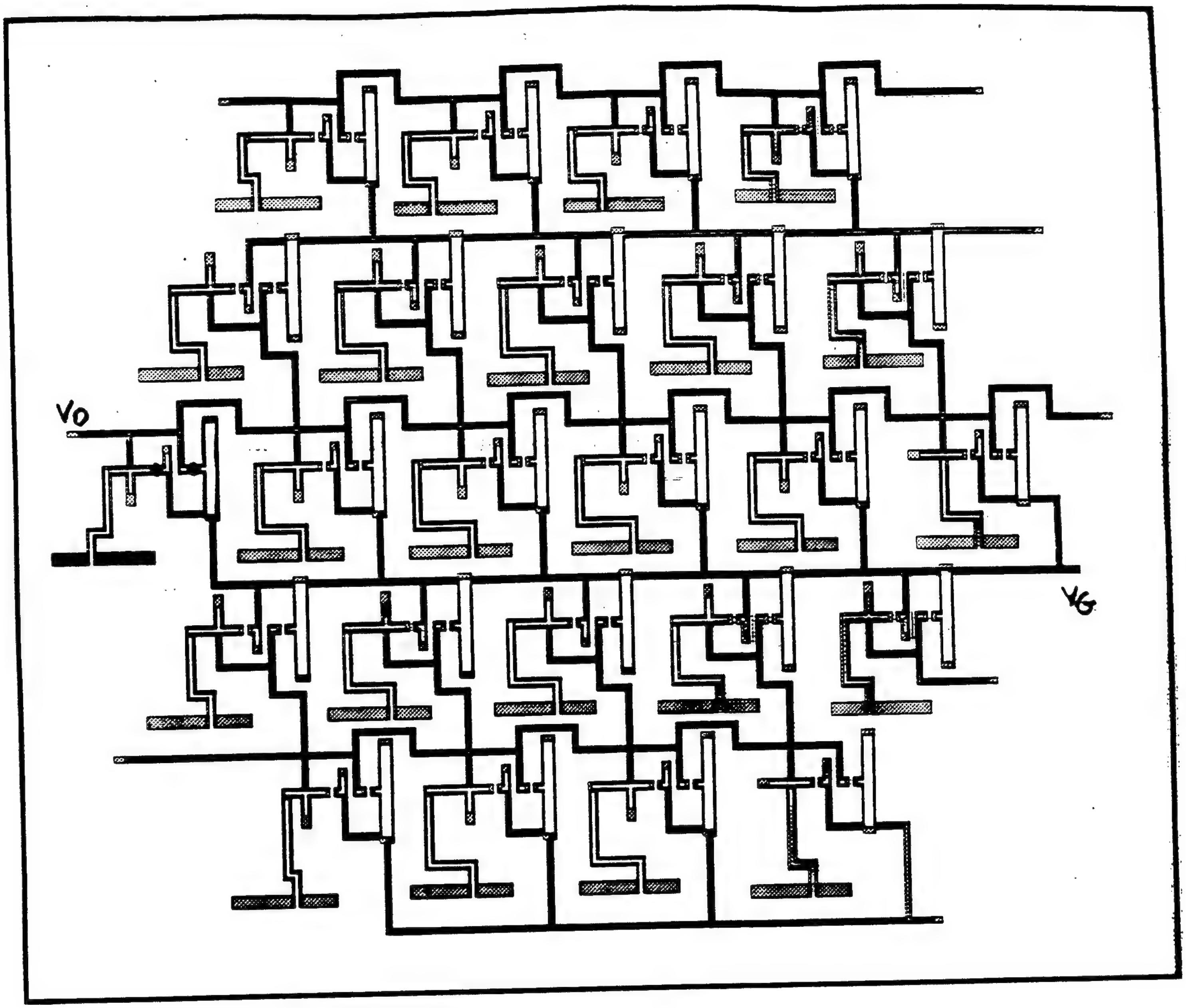

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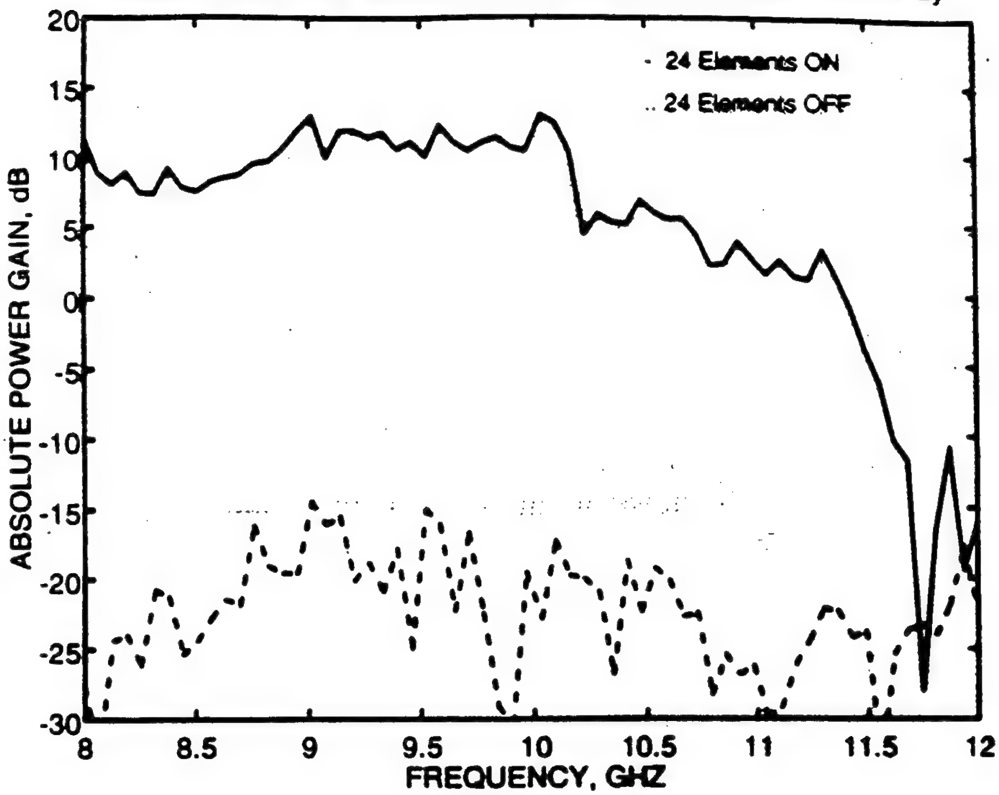
Quasi-Optical Grou

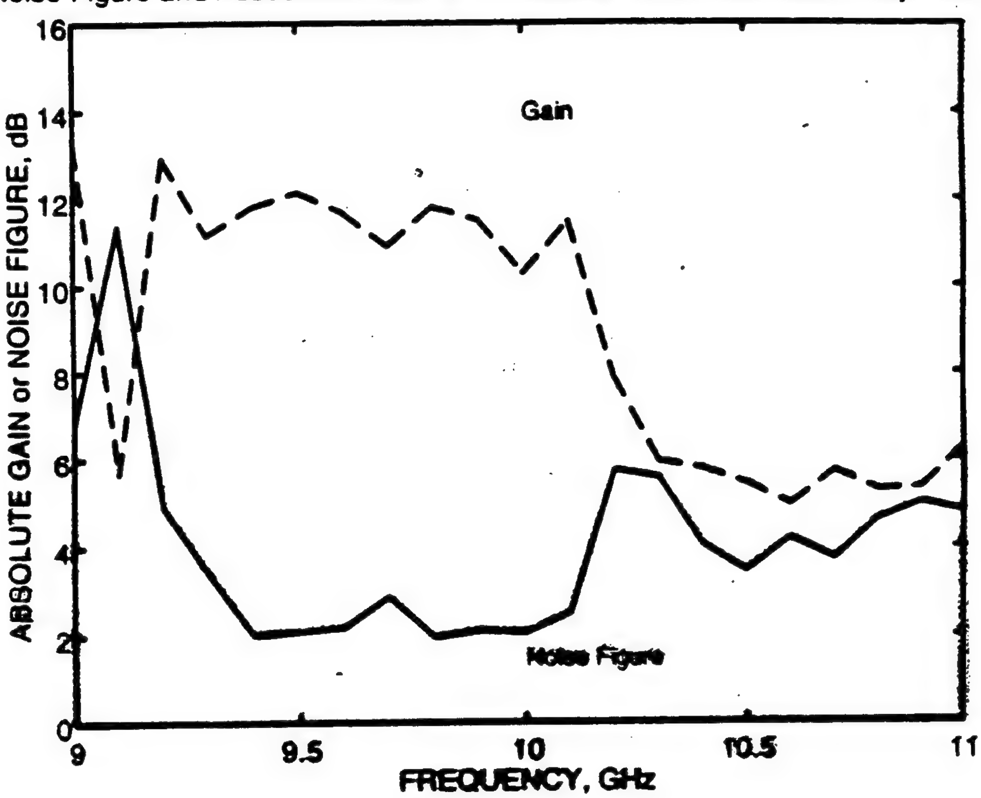
Absolute Gain and Isolation for 24-Element CPW LNA Lens Array



3 dB BW = 11%

ISOLATION > 25d

Noise Figure and Associated Gain for 24-Element CPW LNA Lens Array, Low Bias



NF_{min} = 1.9 dB @ 9.8 GHz

G_{Assoc} = 11.8 dB

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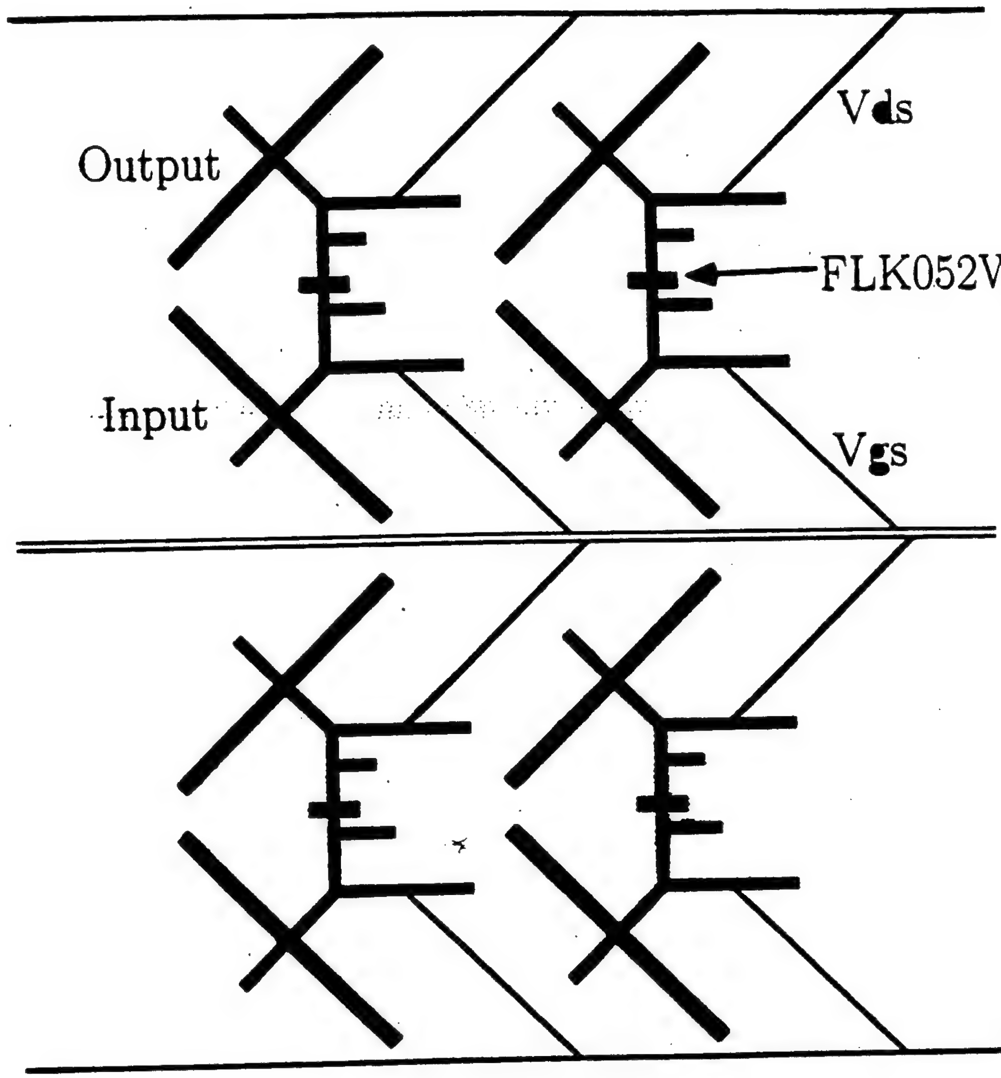
The Quasi-Optical Class-E Power Amplifier



Single Element:
0.7W @ 5 GHz
PAE = 70%

2x2 Array: 2.4W, 64%

- No vias
- No lumped elements
- Good heat sinking
- Polarization isolated
- Broadband structure

~80% POWER-COMBINING EFFICIENCY

Quasi-Optical Group

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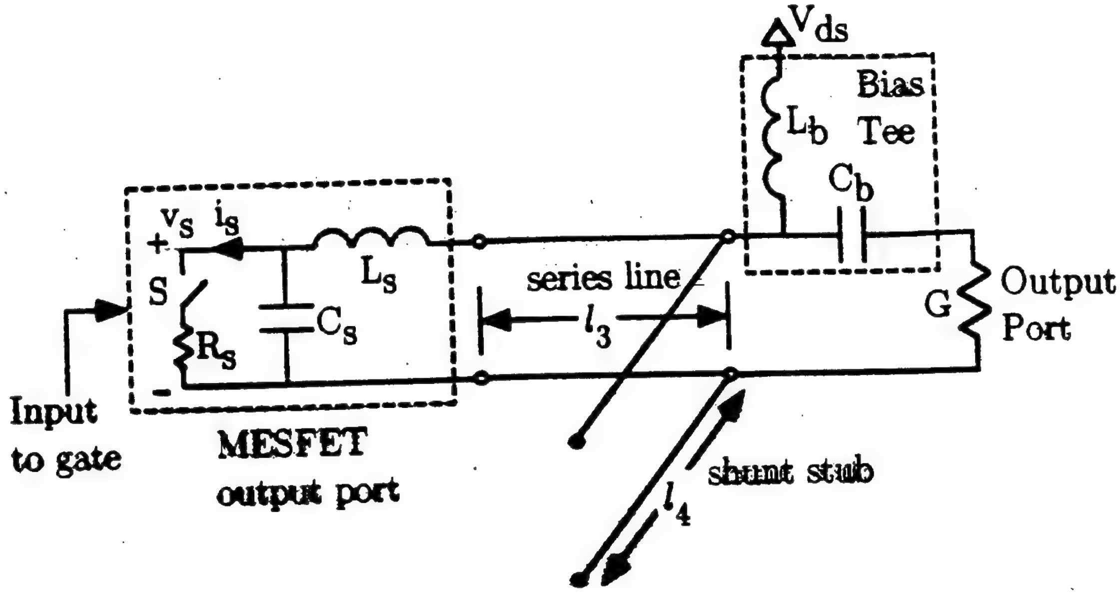
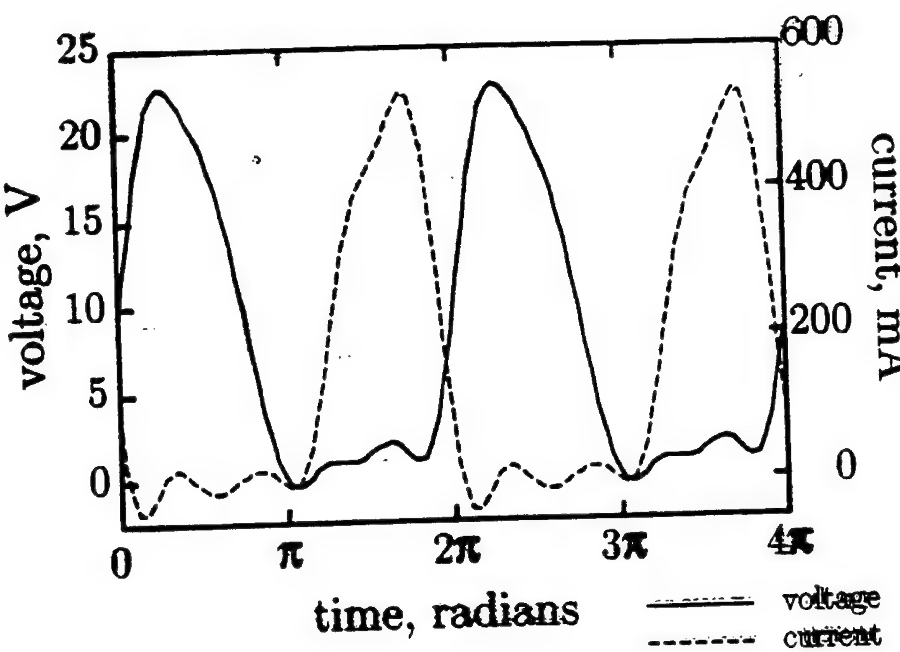
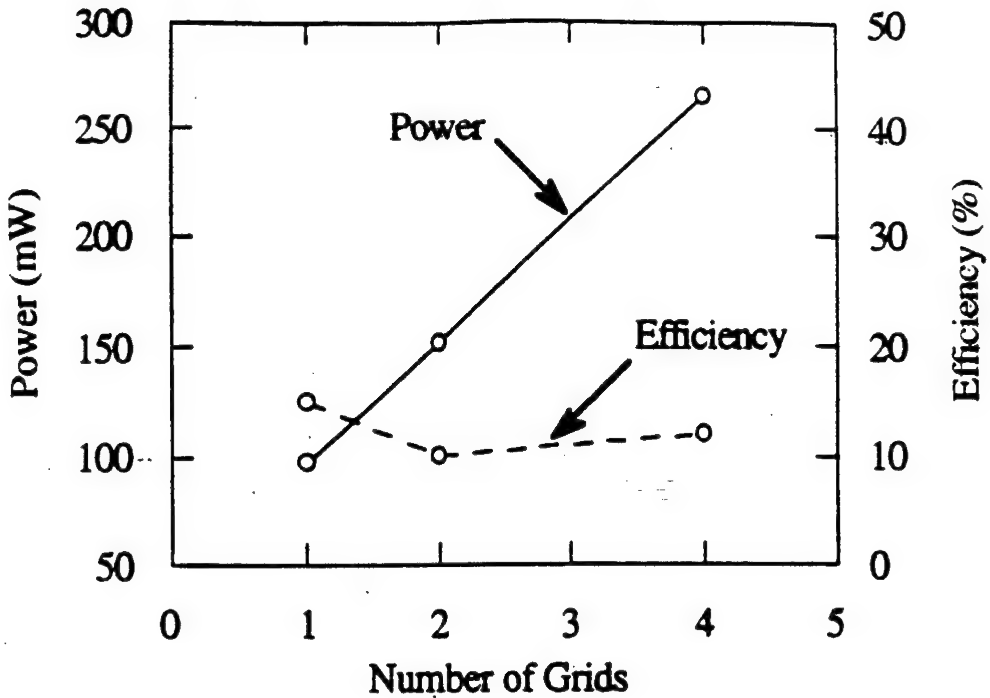
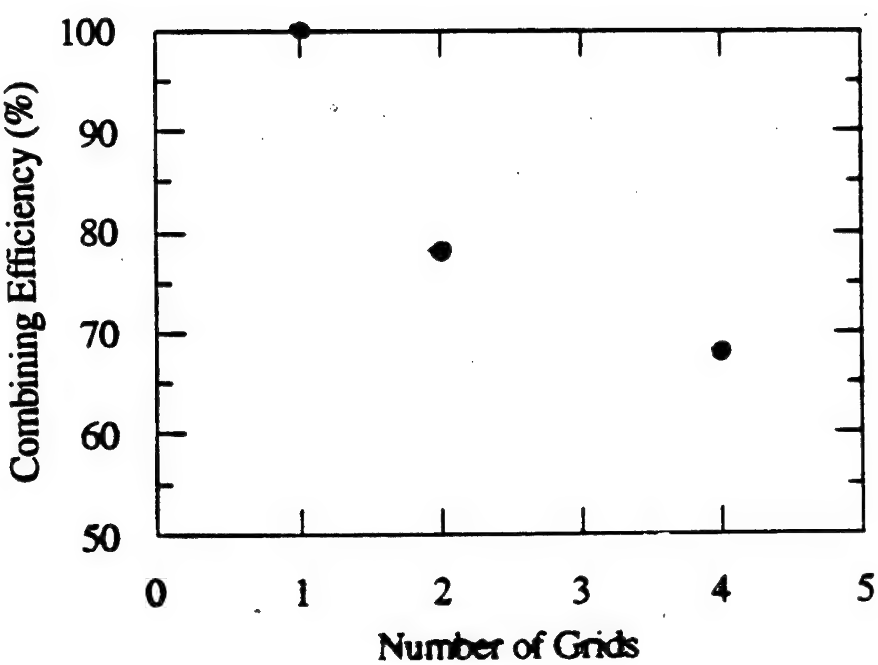
Harmonic Balance Circuit Simulations Using an Ideal Switch Model at 5 GHz

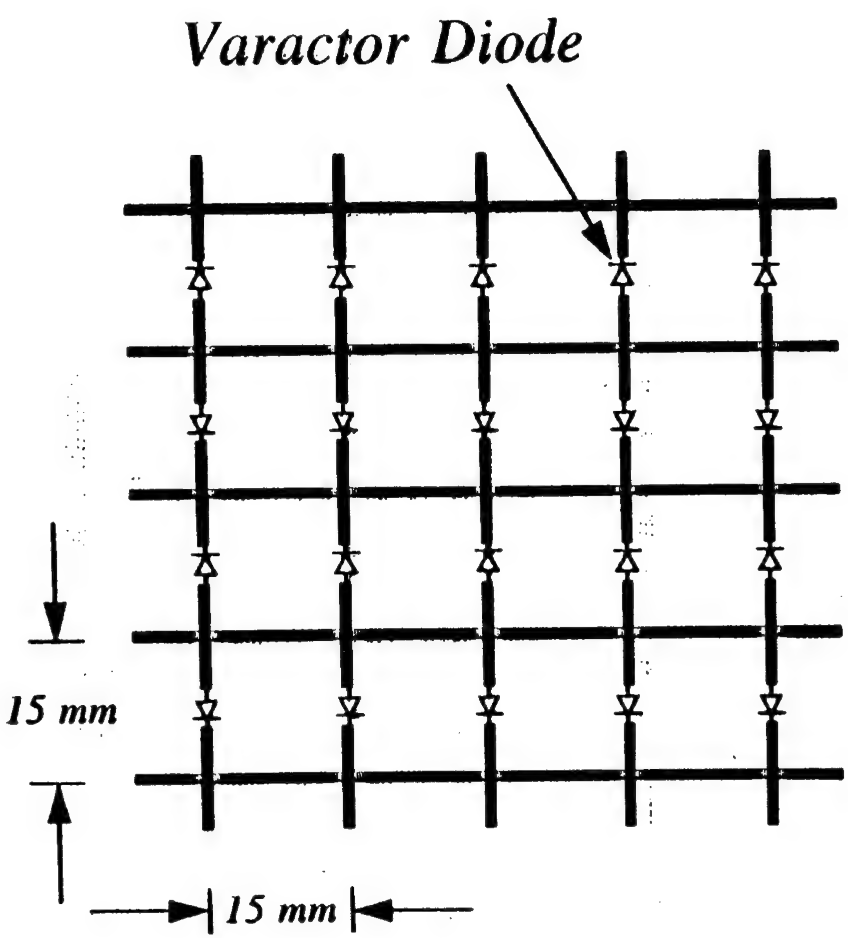


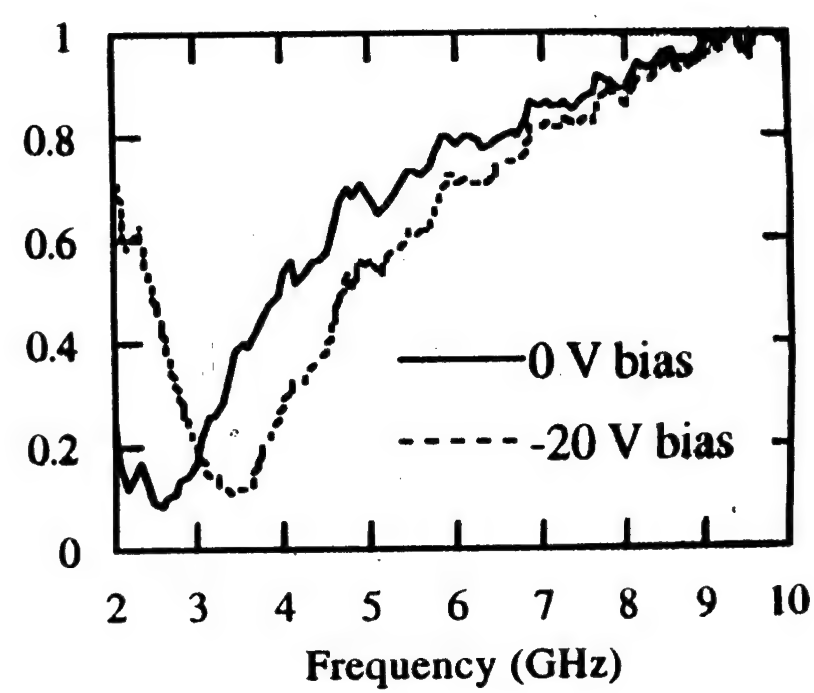



300
250
200
150
100
50
Power (mW)
50
40
30
20
10
0
Efficiency (%)
Power
Efficiency
0
1
2
3
4
5
Number of Grids


100
90
80
70
60
50
Combining Efficiency (%)
0
1
2
3
4
5
Number of Grids

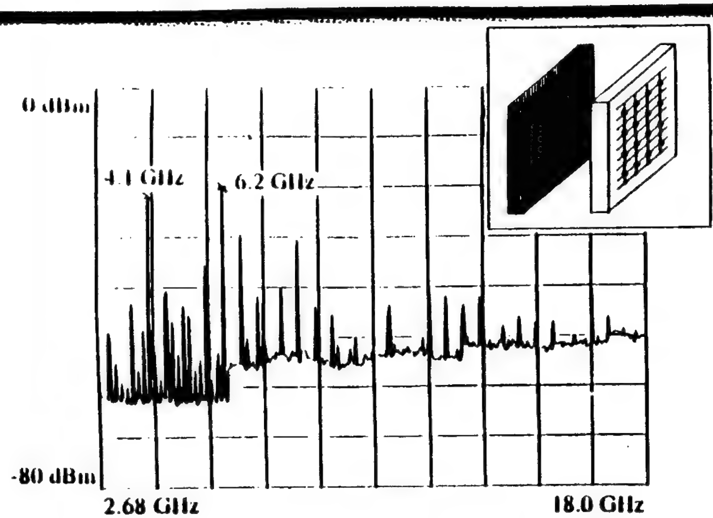
Tunable Transmission Filter



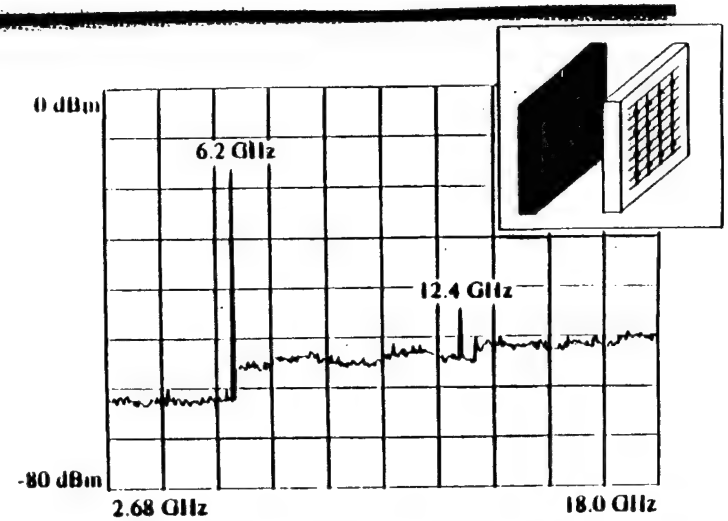


30% tuning bandwidth

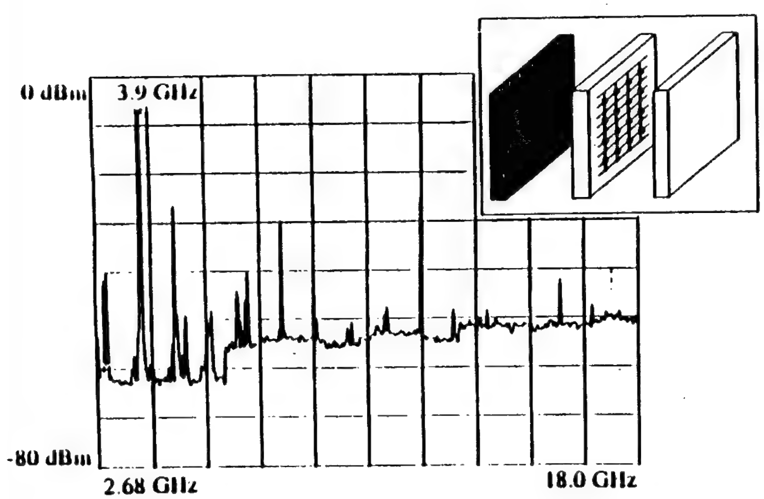
Mode-Selective Grid Oscillator



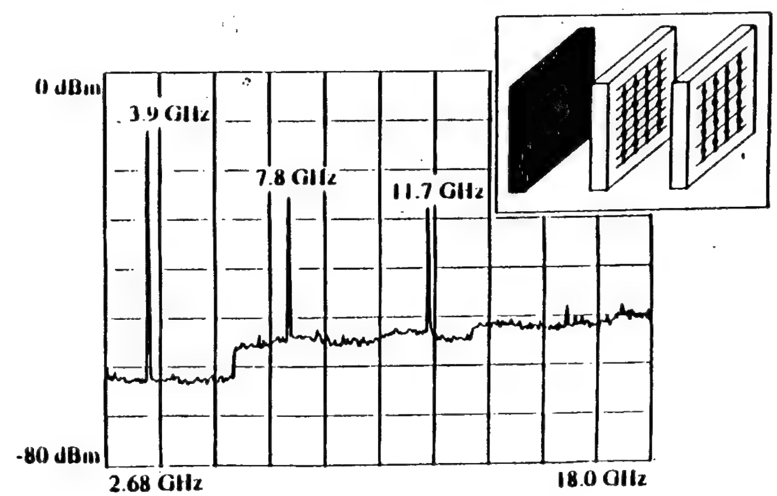
Unlocked spectrum with two competing modes



Locked mode achieved through gate bias adjustment



Unlocked spectrum with a partially reflecting front mirror



Locked mode achieved using a variable-reflectance mirror

Quasi-Optical Isolator

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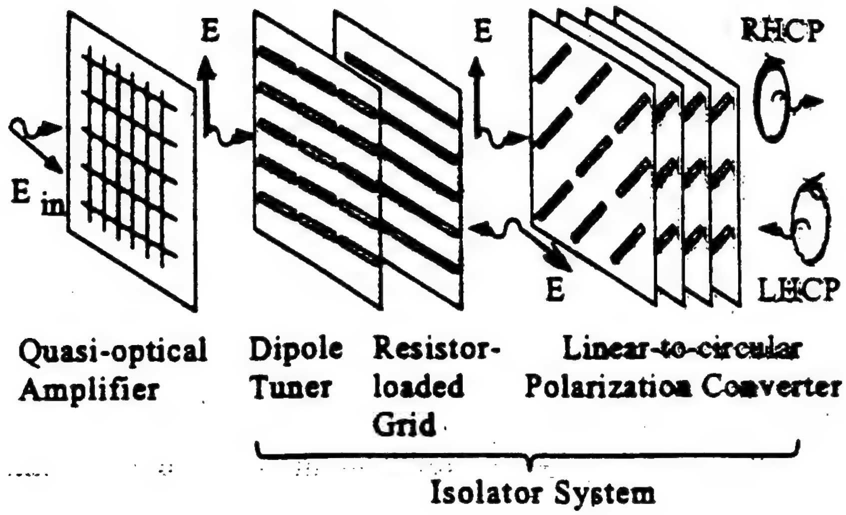
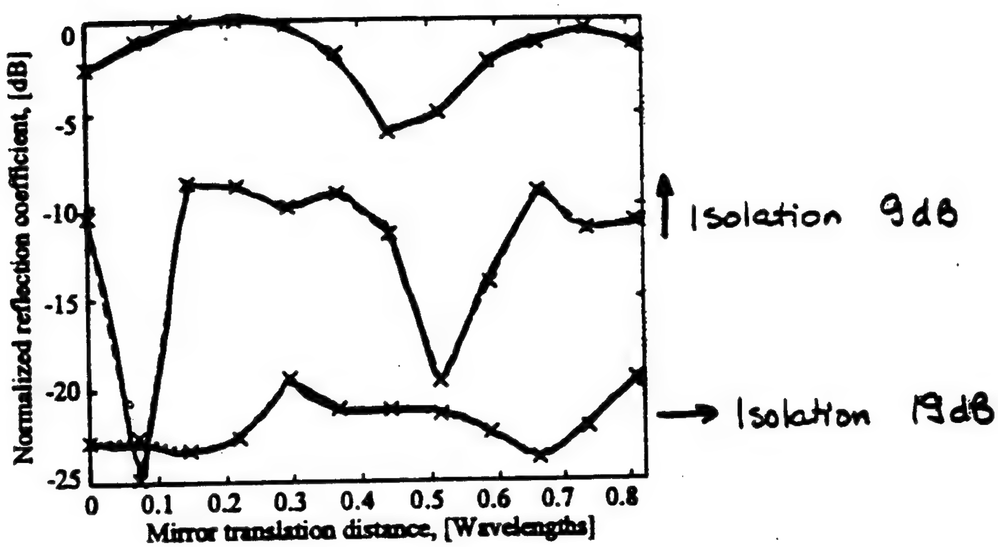
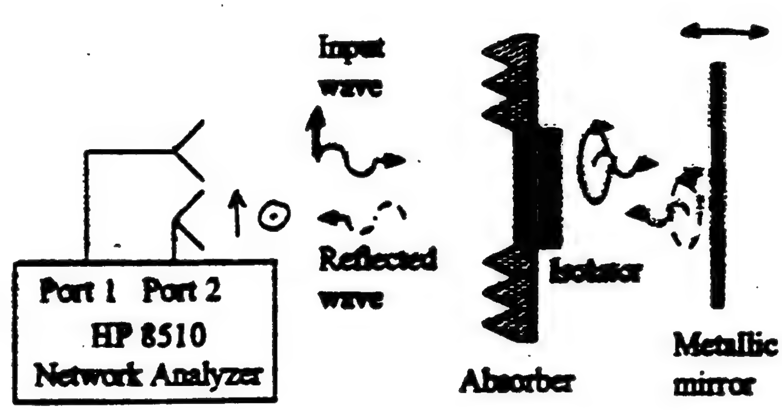


f = 8.93 GHz





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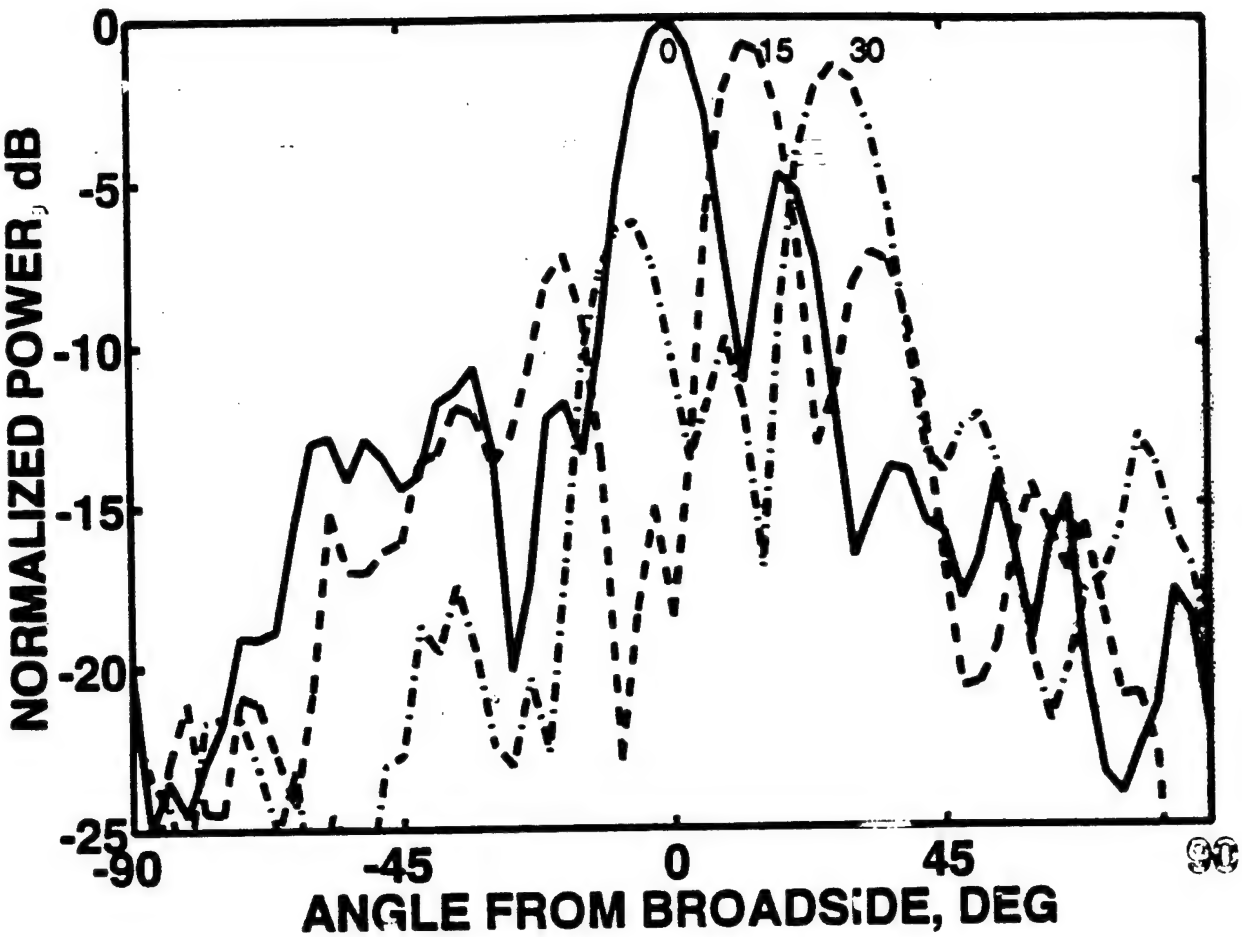
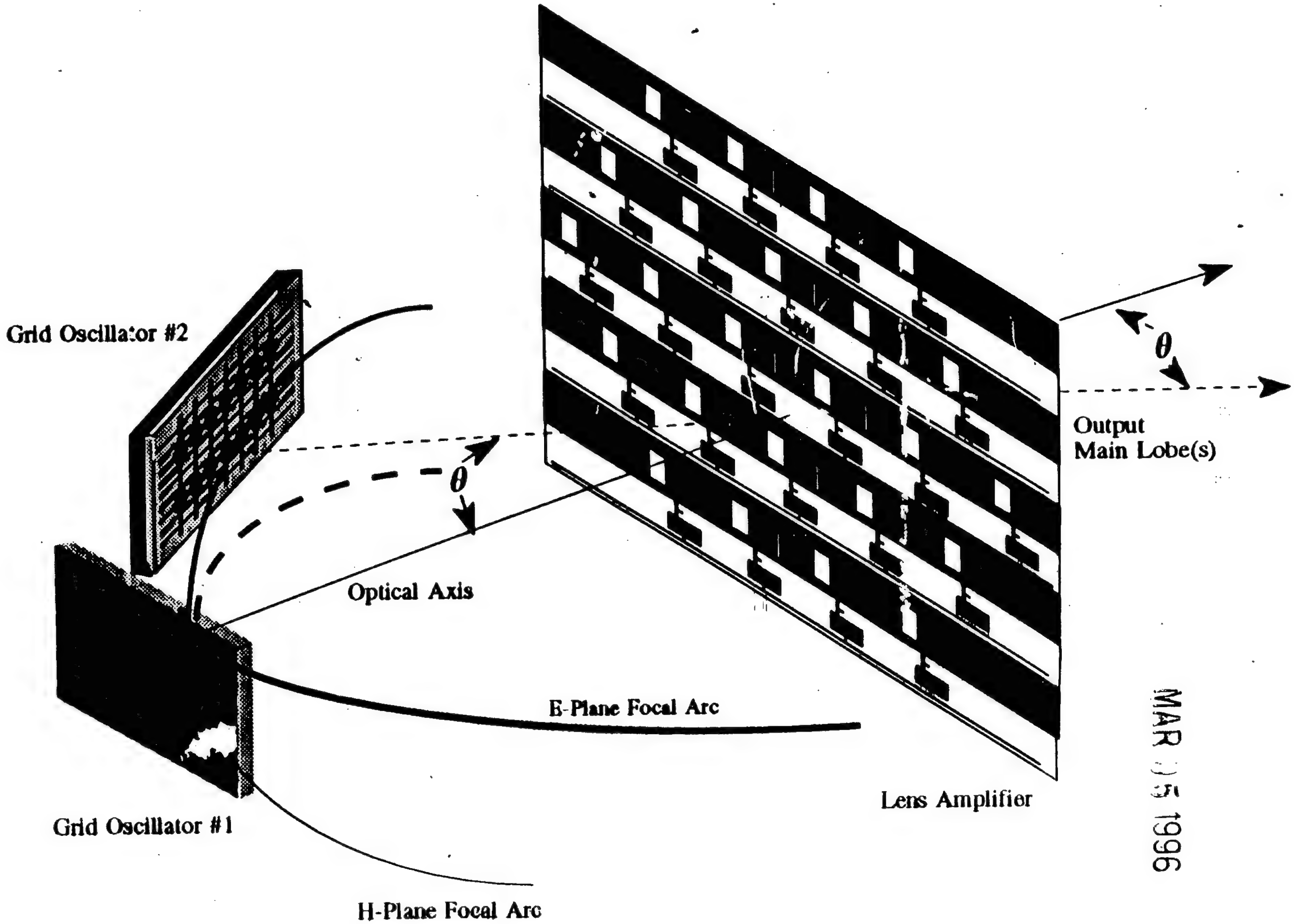


0
15
30
NORMALIZED POWER, dB
0
-5
-10
-15
-20
-25
-90
-45
0
45
90
ANGLE FROM BROADSIDE, DEG


Grid Oscillator #2
Output
Main Lobe(s)
θ
θ
Optical Axis
E-Plane Focal Arc
Lens Amplifier
Grid Oscillator #1
H-Plane Focal Arc

Quasi-Optical Group

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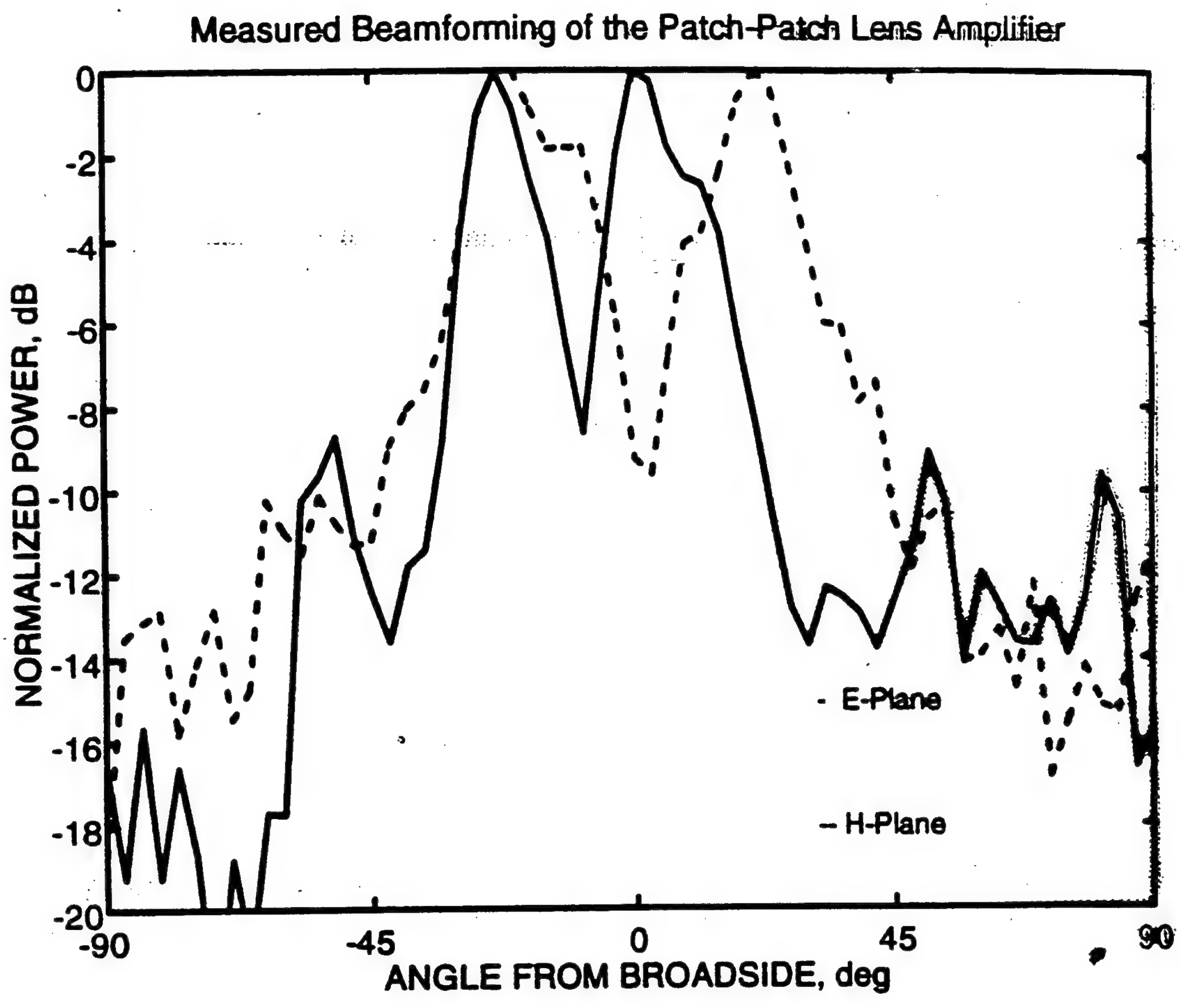

Quasi-Optical Receiver with Angle Diversity

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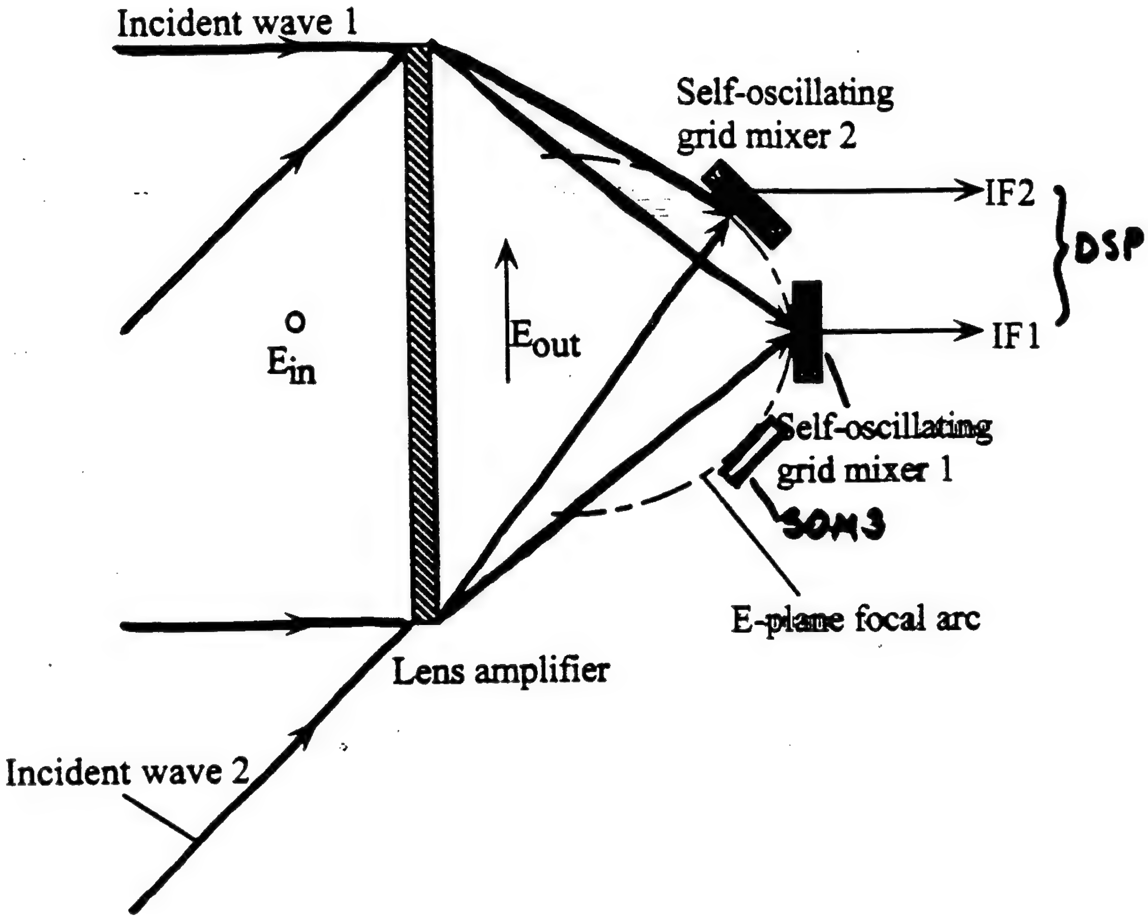
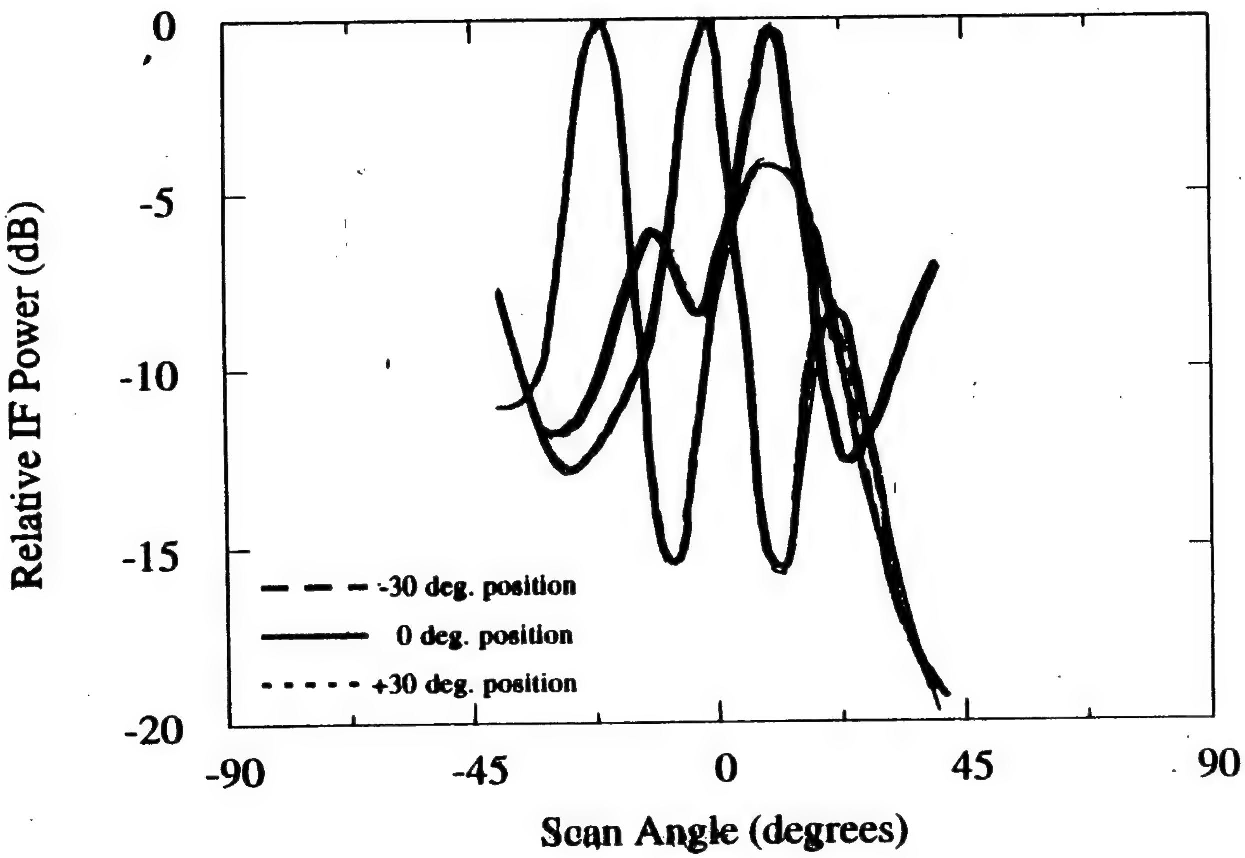


n uncorrelated beams:

$$P_e \propto \left(\frac{n}{S/N}\right)^n$$



Relative IF Power (dB)
0
-5
-10
-15
-20
-90
-45
0
45
90
Scan Angle (degrees)
-30 deg. position
0 deg. position
+30 deg. position

Millimeter-wave Wireless Laboratory

MAR [illegible] 1996

Quasi Optical Arrays for Millimeter-Wave Communication Applications

RICHARD COMPTON

SCHOOL OF ELECTRICAL ENGINEERING

CORNELL UNIVERSITY

ITHACA NY 14853

HTTP://WRG.EE.CORNELL.EDU/

Outline

1. Applications
   - PCS, MMDS, LMDS, 60 GHz, (Point-to-Point)
   - Digital Battlefield
2. Key Technical Parameters
   - Power/Filtering/Spectral Efficiency/Mechanical Design
3. Quasi-Optics
   - Circular Arrays/Reflectors/Diversity
   - Modulation FSK/PSK
4. Technology Barriers
   - Design/Measurement
   - Low-Cost Manufacture
5. Research Strategies

TELECOMMUNICATIONS

Cable Television Without The Wires

A 5-in. antenna receives the microwave signal.

BY STEPHEN A. BOOTH, Contributing Editor

PM Photo by J.R. Rost

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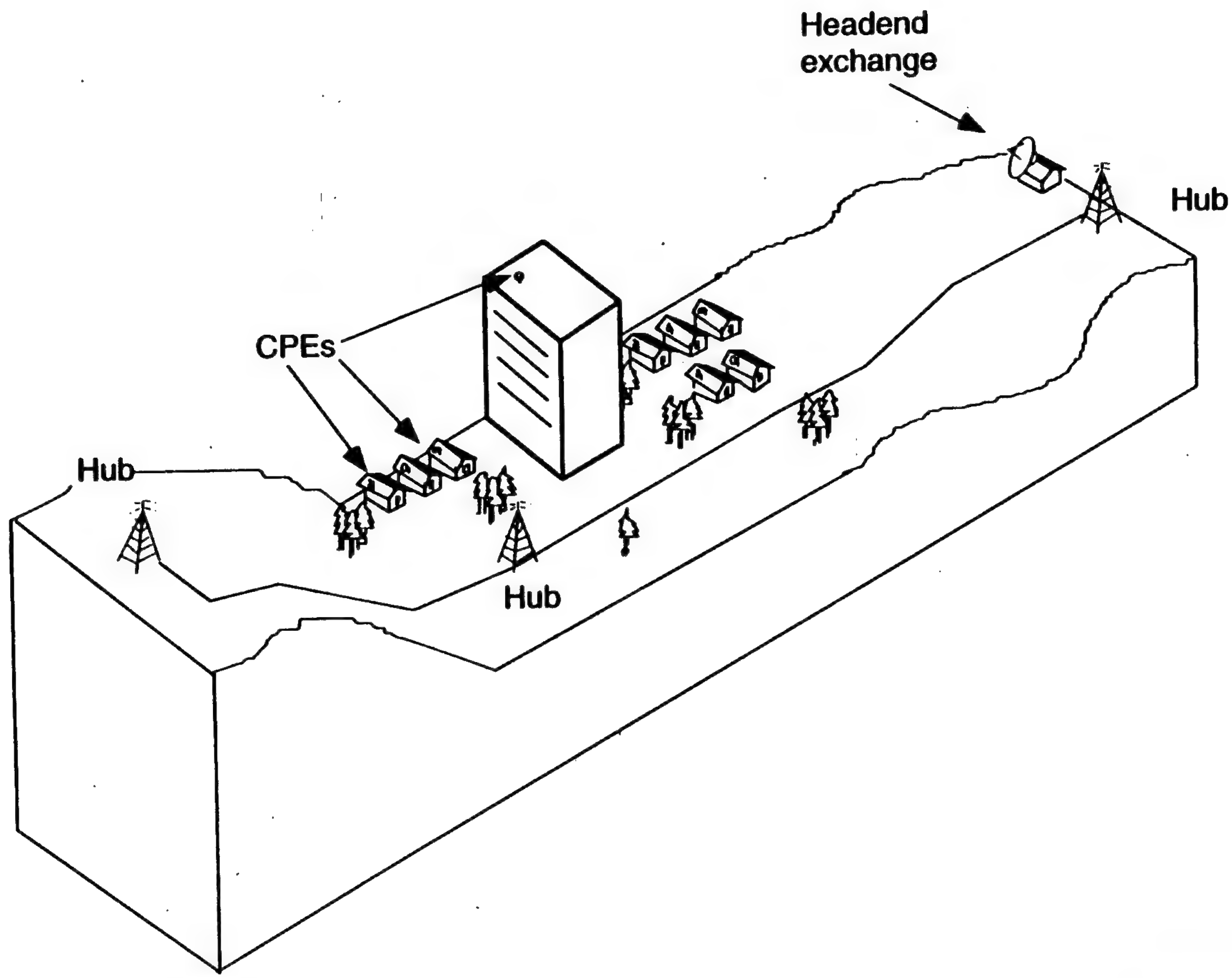
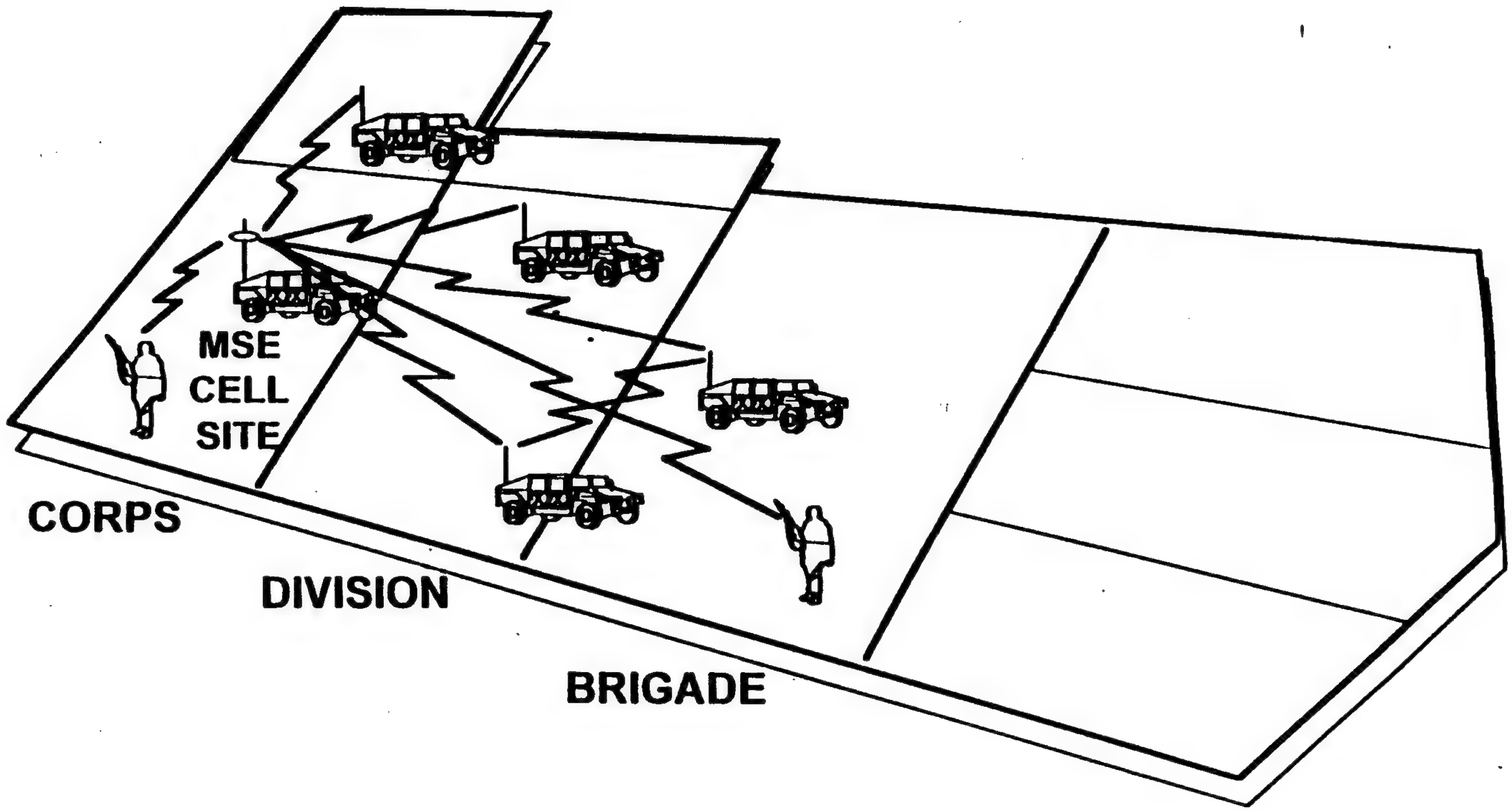
Local Multipoint Distribution Service (LMDS)




MSE
CELL
SITE
CORPS
DIVISION
BRIGADE

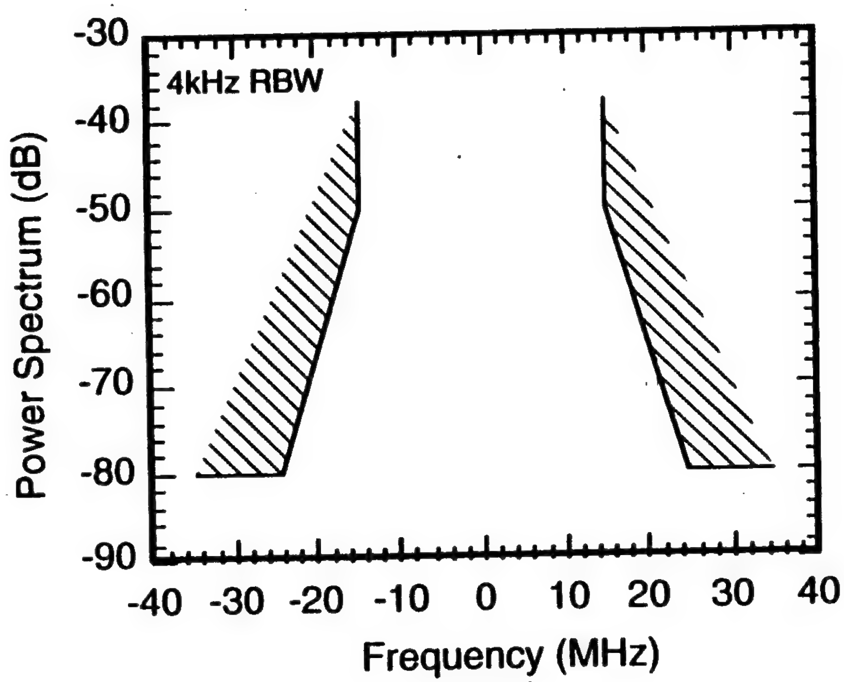
1996

Power Requirements

75 MBPS 60GHz 10 Watt Transmitter

Hub Transmission	10	dBW
Transmit Antenna Gain	12	dB
Path Loss (100m)	-108	dB
Noise Figure	-6	dB
Receive Antenna Gain	6	dB
Received Power	-86	dBW
Noise (50MHz)	-127	dBW
C/N	41	dB
Required C/N	15	dB
Fade Margin	26	dB

Filtering


4kHz RBW
Power Spectrum (dB)
-30
-40
-50
-60
-70
-80
-90
-40 -30 -20 -10 0 10 20 30 40
Frequency (MHz)

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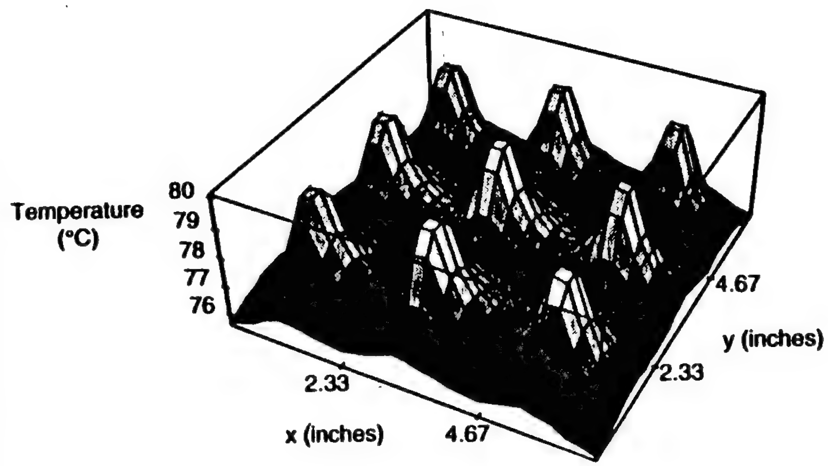
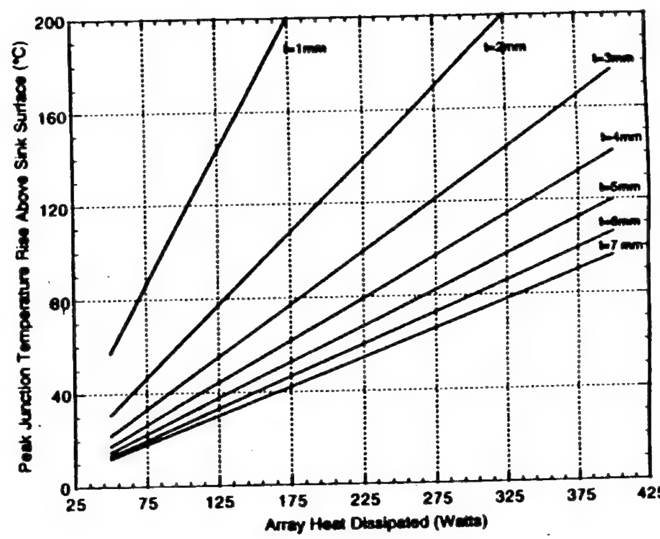
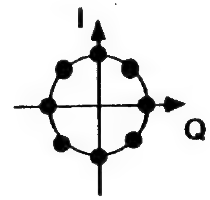
Thermal Control

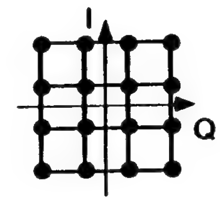




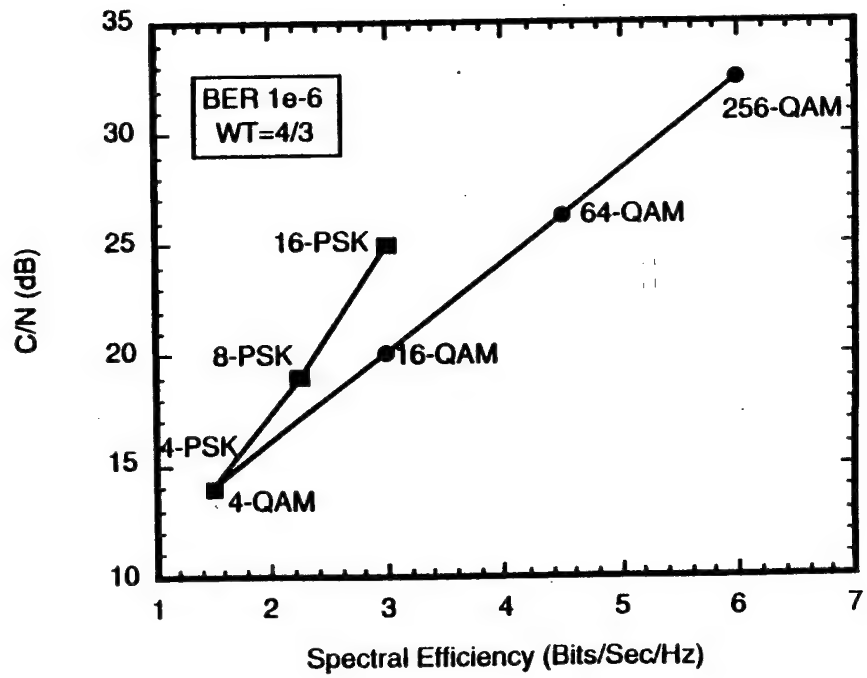
Spectral Efficiency



8-PSK



16-QAM



$$V(t) = I(t)\sin\omega t + Q(t)\cos\omega t$$

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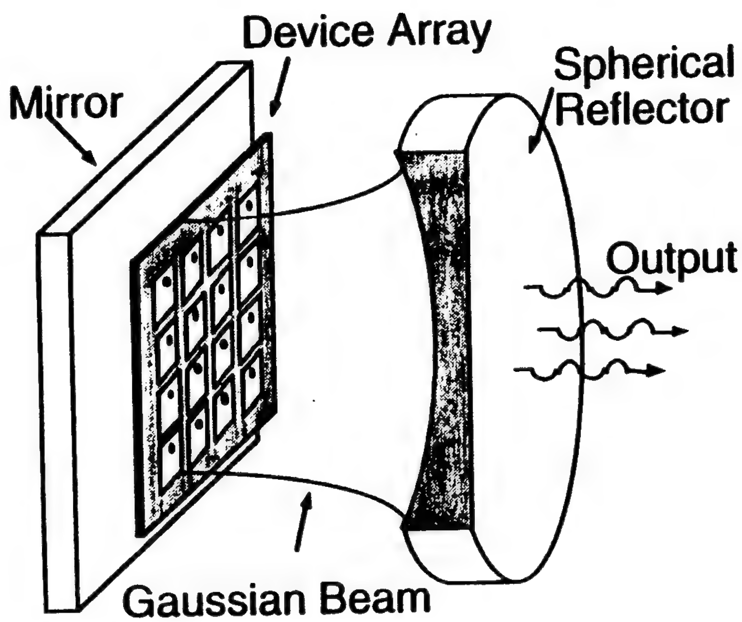
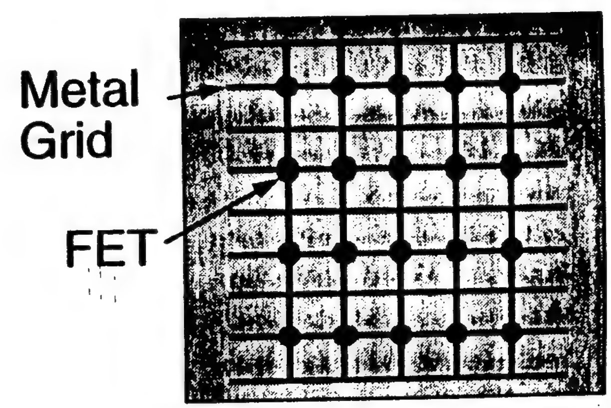
Quasi-Optical Arrays

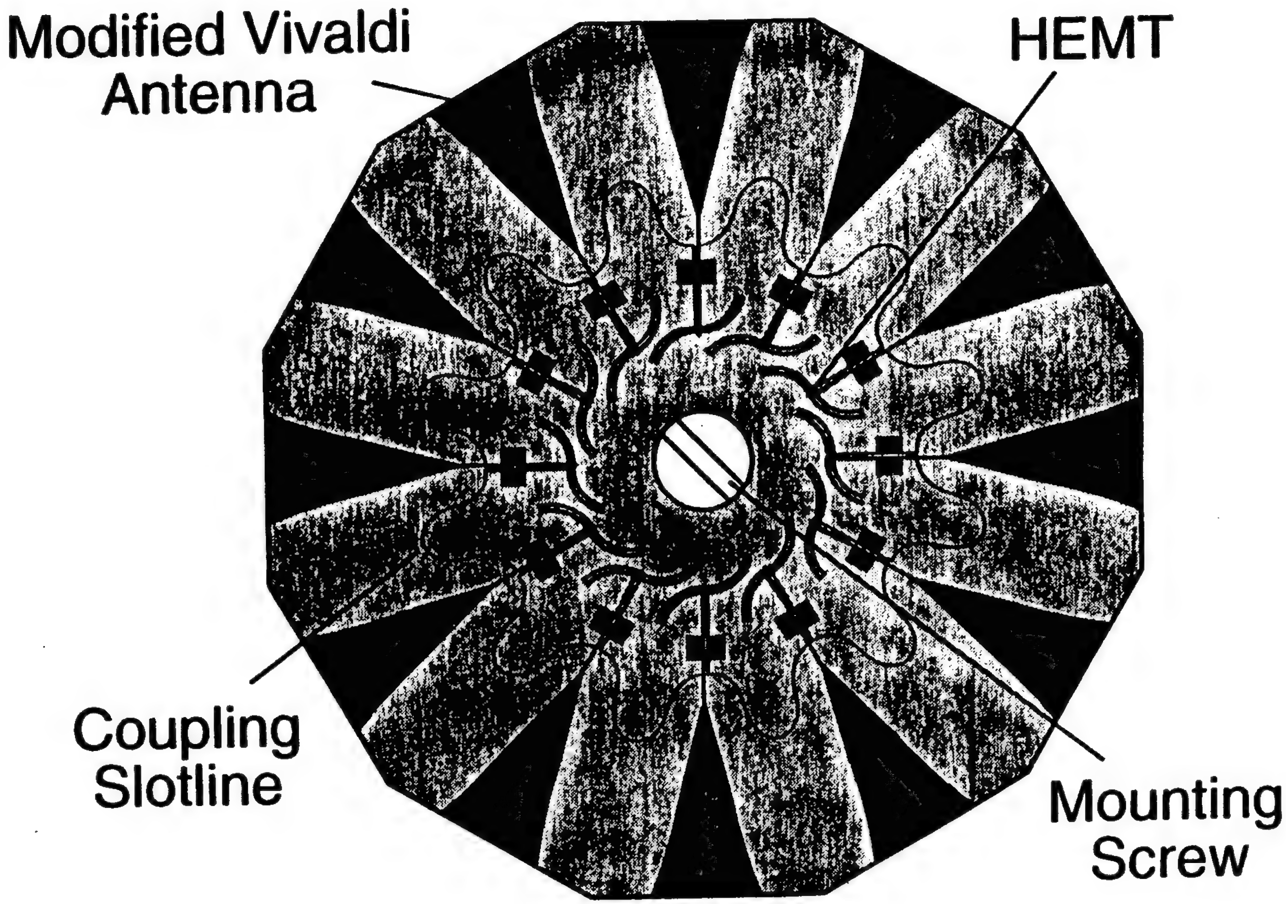


Coupled Oscillator Array

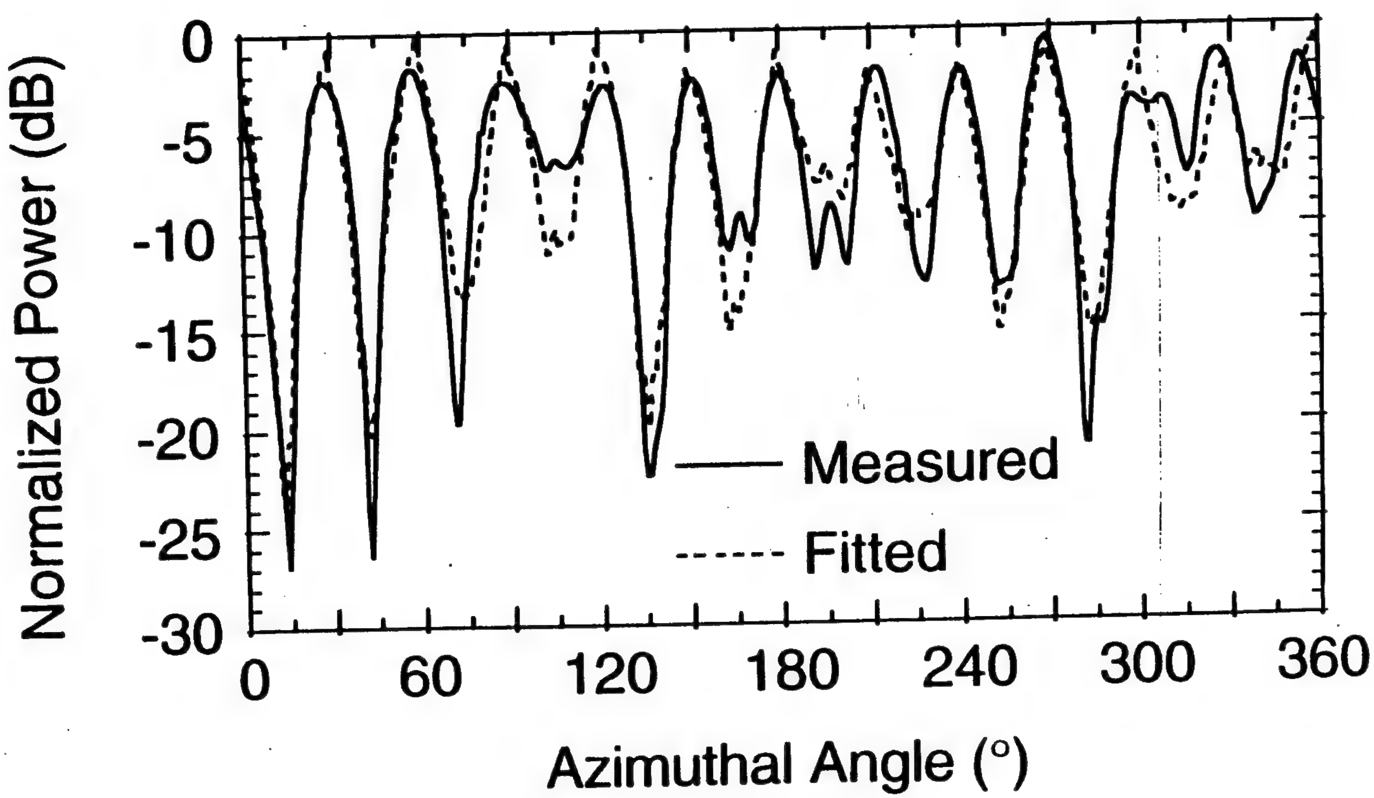


Distributed Grid Array

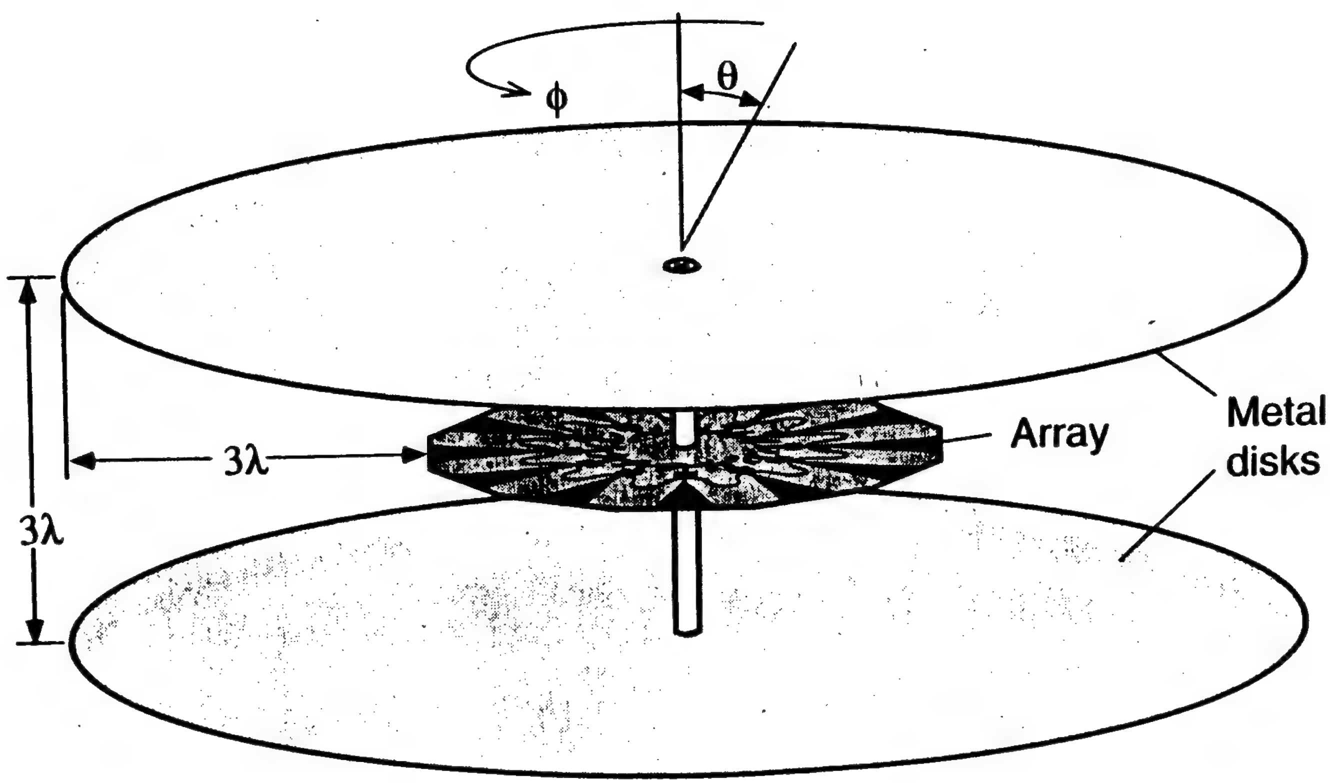
Circular Array



Array Pattern



Pattern Enhancement



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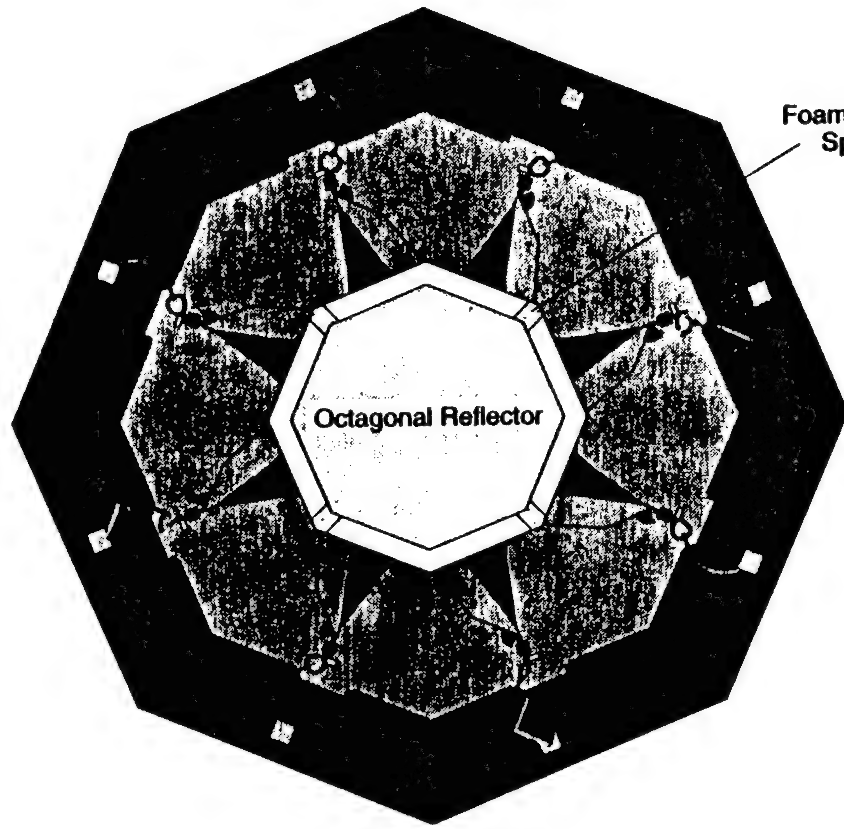
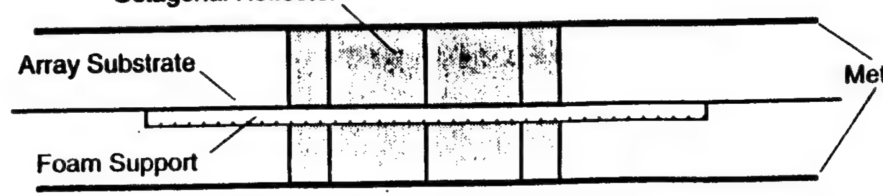
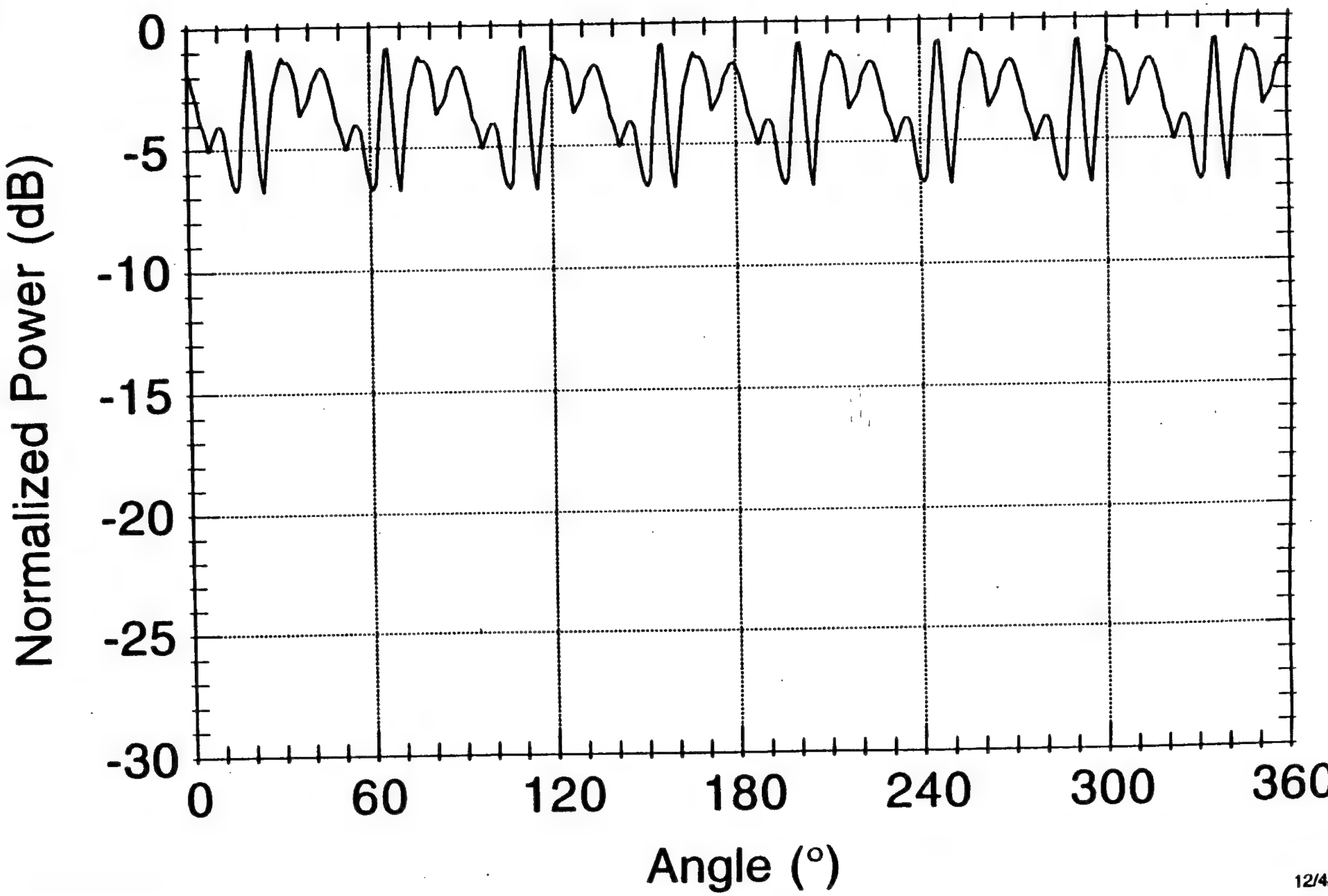
Reflector Enhancement



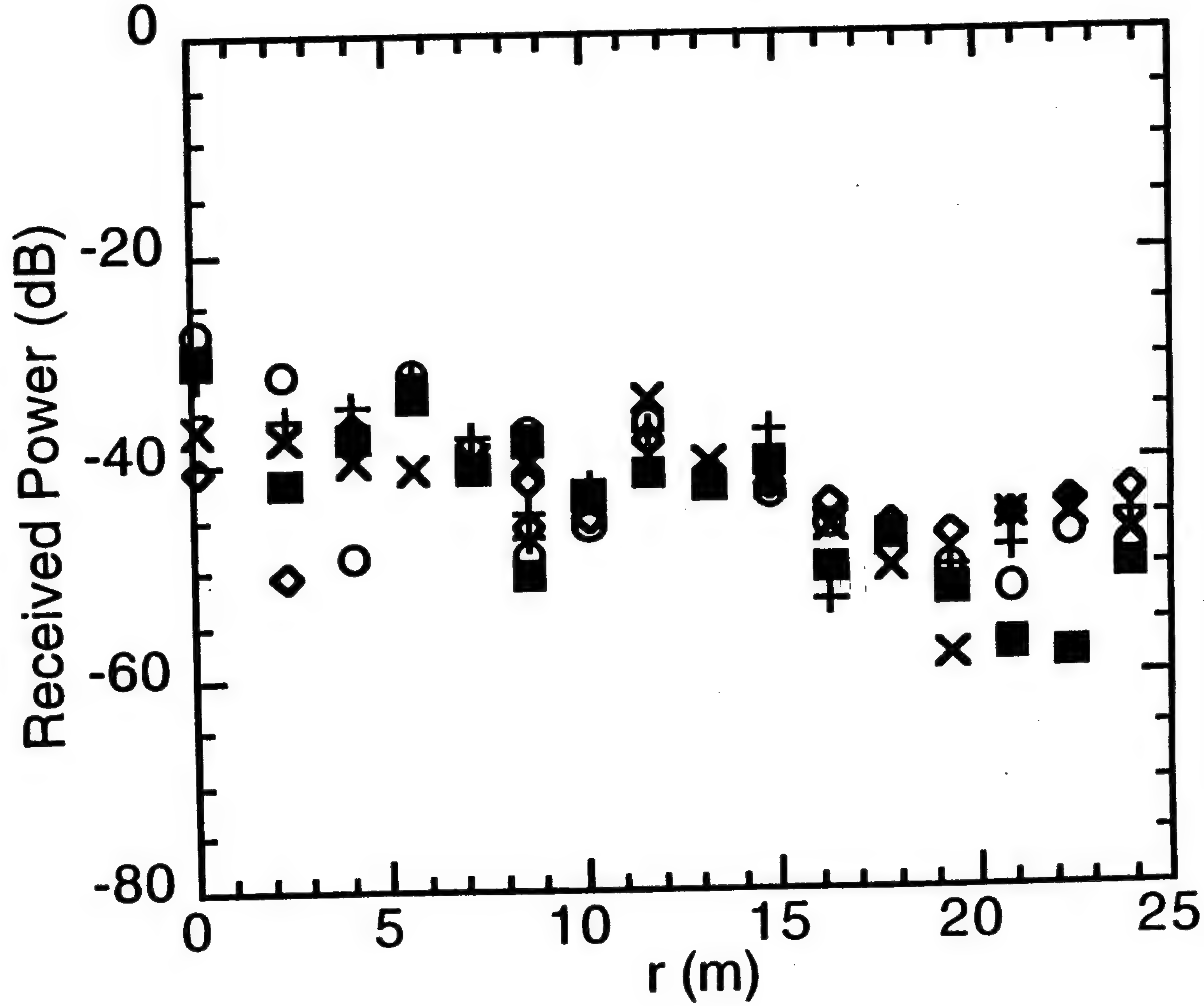


Reflector Enhancement

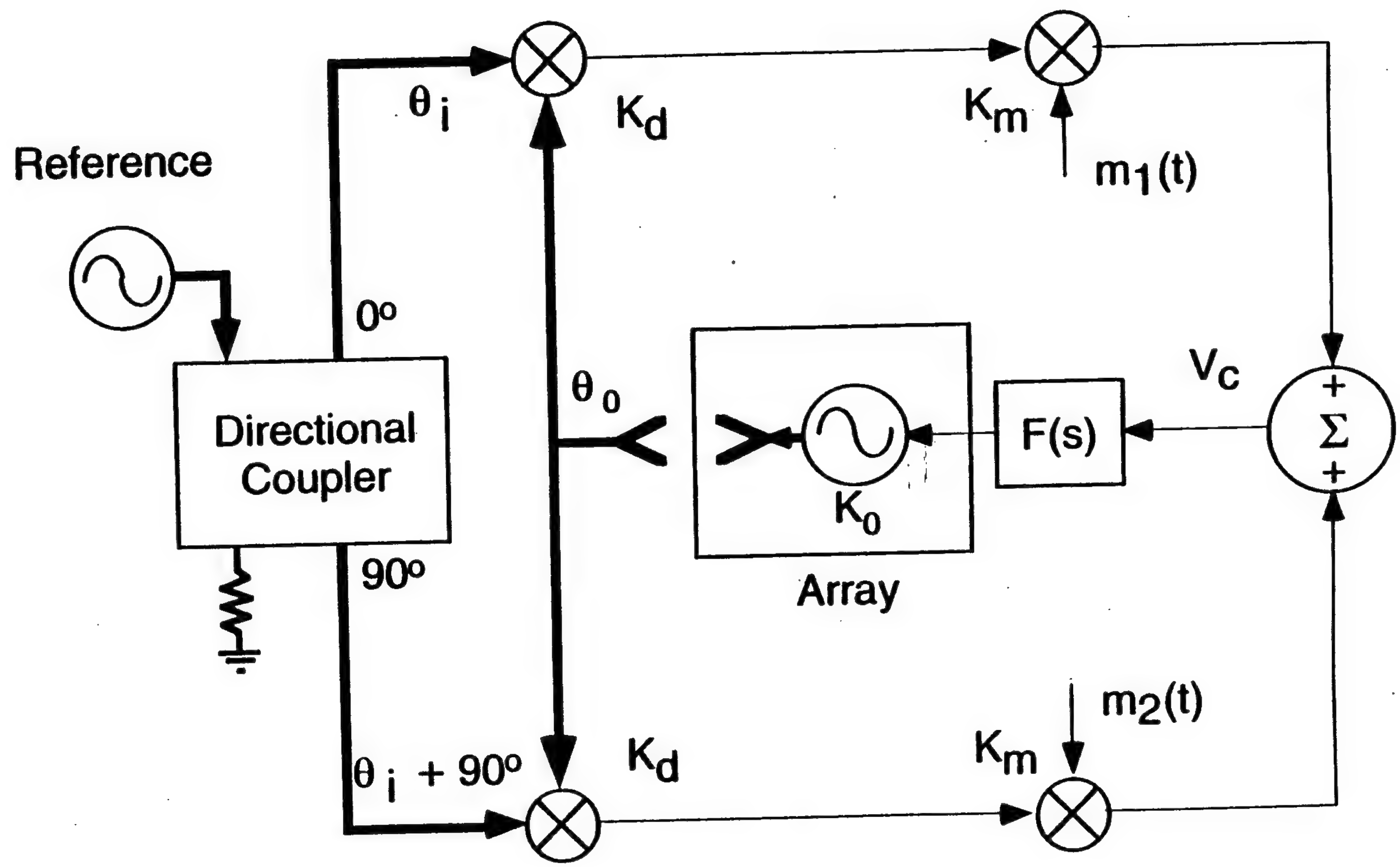


Millimeter-wave Wireless Laboratory

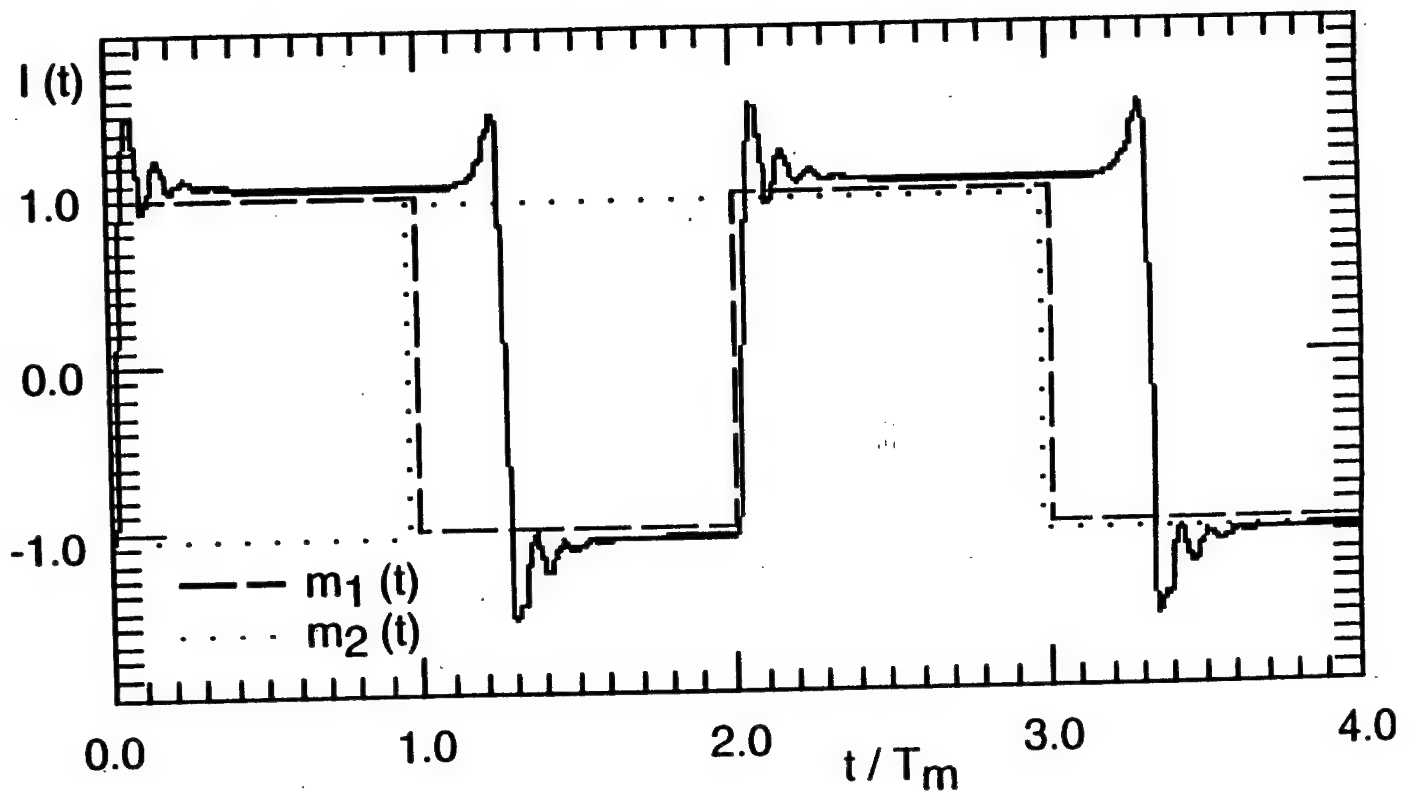
Diversity



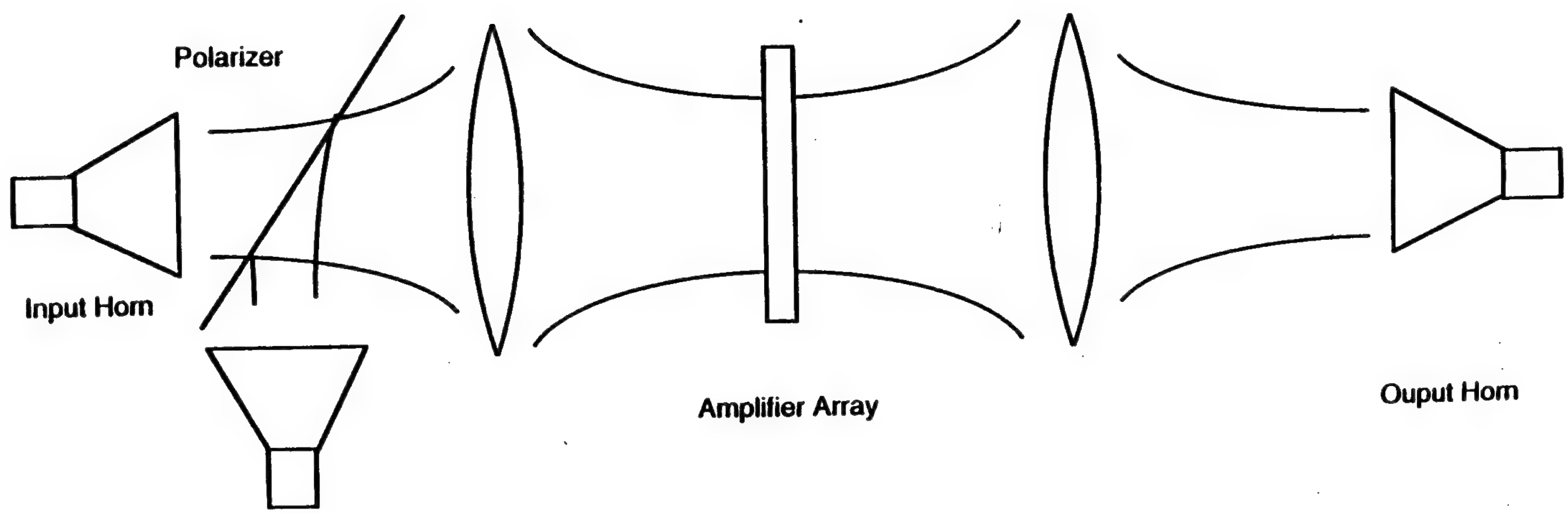
QPSK Modulator



Non-Linear Modelling

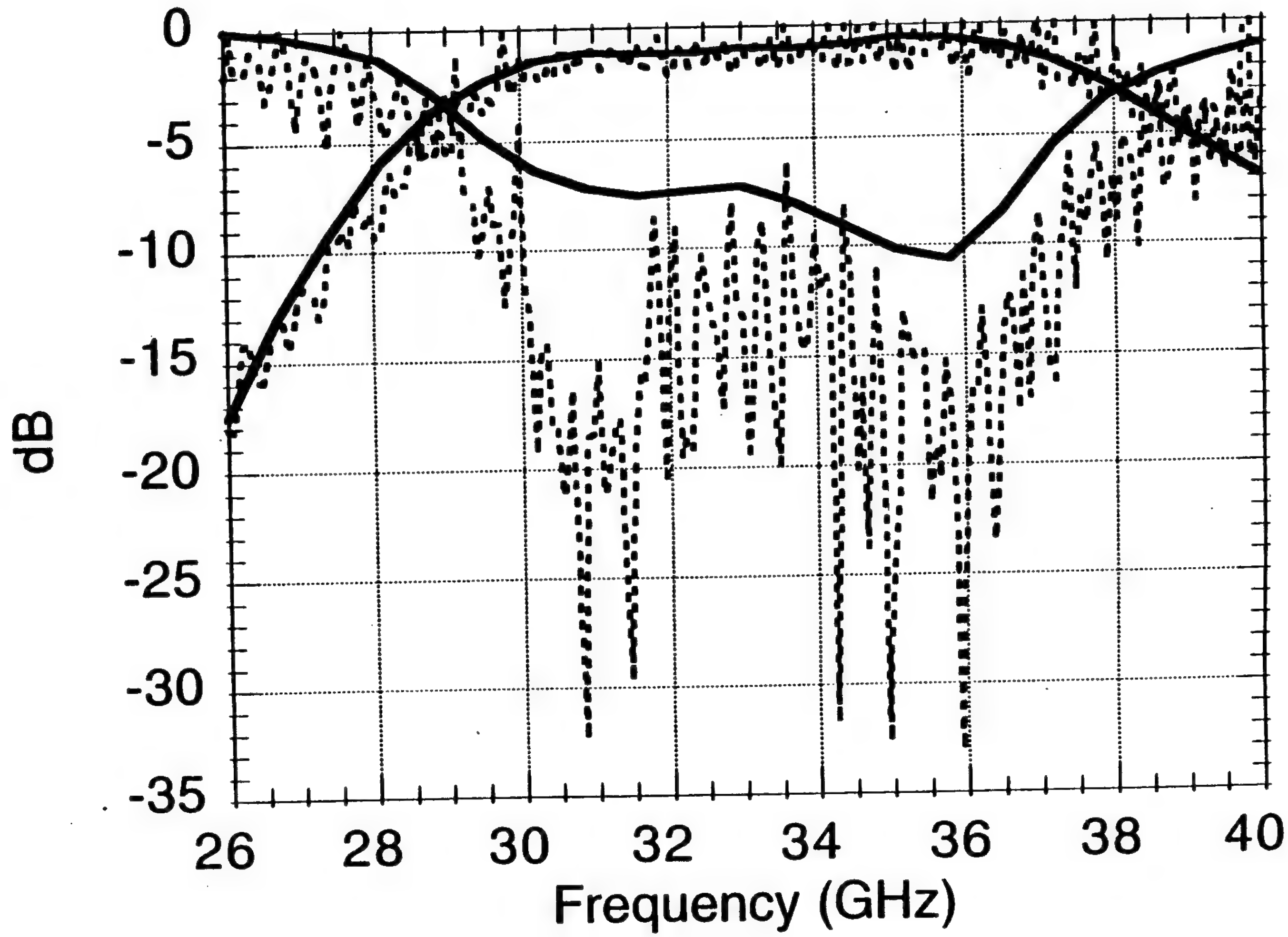


Measurement Layout



Millimeter-wave Wireless Laboratory

Measurement



Research Strategies

1. System Level Evaluation of Quasi-Optics
   — Broadband Trial
2. Industry/University Program
   — Service Providers (Cable/RBOC)
   — Equipment Manufacturers
   — Microwave Companies
   — University
      — Coding
      — VLSI
      — RF Circuits and Devices

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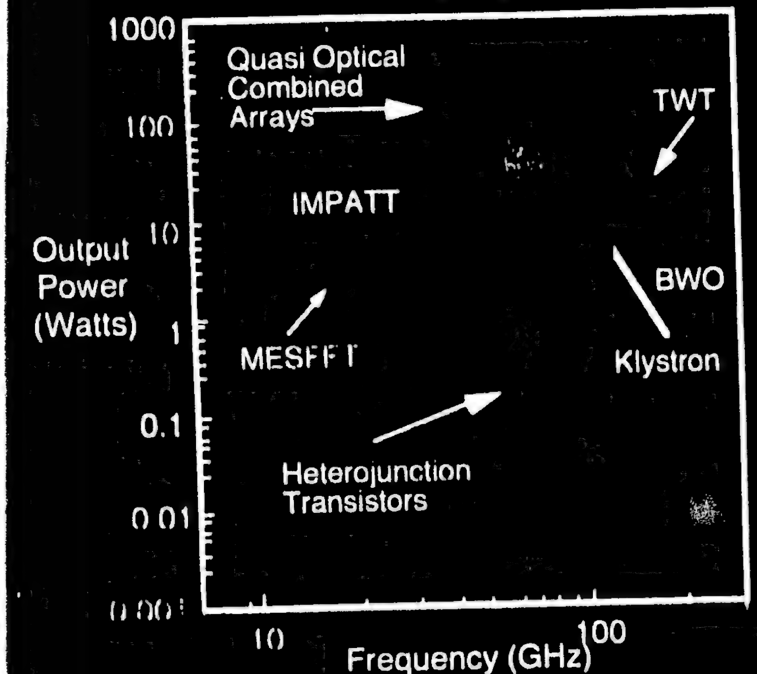
Quasi Optics
Two Technology Breakthroughs

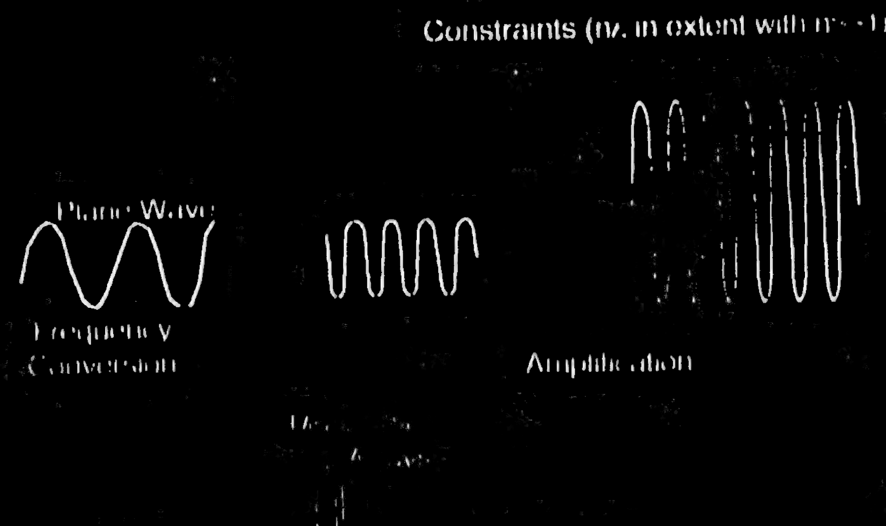
Power



- Solid State Sources from Tens of watts to Thousands of watts
- Microwave and Millimeter Wave Bands
- Gracefully Degrading

  High Power with Solid State

Phased Arrays



- Wafer Scale Integration of Simple Identical Circuit Cells
- 16 : 1 to 3000 : 1 Reduction in Module Count
- Lower Cost by 3 to 10 Times
- Upper Microwave and Millimeter Wave Bands

  Enables Phased Arrays at MMW

MARTIN MARIETTA

SA093-0238-02

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MMW Quasi-Optic Power Applications

Area	Example Programs	Bands	Power Watts	Prod Nrs	When
Smart Weapons	Longbow, JDAM P3I, BAT, LOCAAS, Guided Projectiles, MSTAR	Ka, W	2-20	10,000's	'95-'05
Hit-to-Kill Seekers	Erint/PAC3, JSSAM, Corps SAM, Helo A/A, ADKEM, HARM	Ku, Ka, W	50-2000	1,000's	'00-'10
All Wx Rot Wing Strk/Recce	AH-64, AH-66, SH-60, OH-58	Ka, W	10-100	100's	'95-'05
All Wx Fixed Wing Strk/Recce	F-15, F-16, F-18, F-117, B-1, B-2	Ku, Ka	> 1000	100's	'00-'10
Ground FCR	M1, M2, CIWS upgr, Base Def	Ka, W	50-200	100's	'00-'10
Comm	Xlinks, Downlinks, Uplinks	Kt, Q, V	5-500	1,000's	'00-'10

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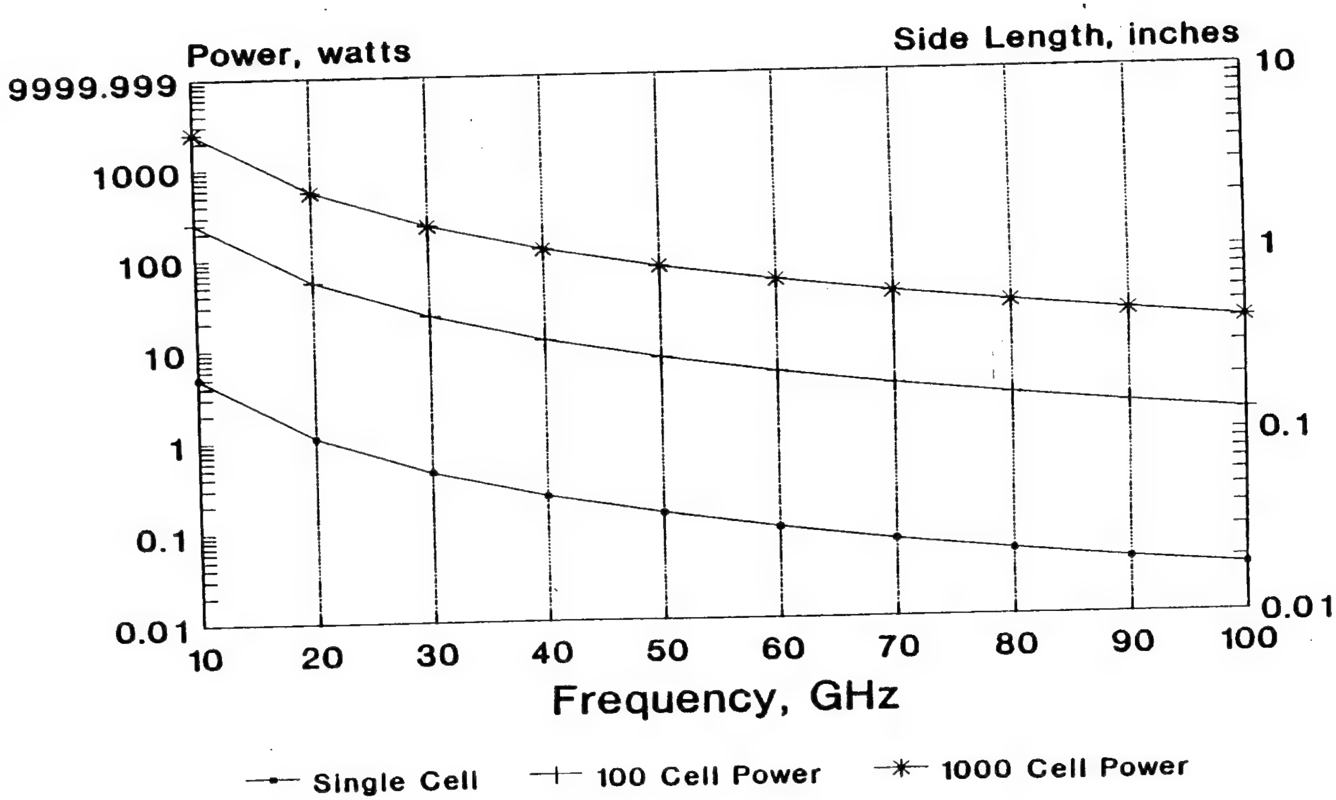
Grid Array Power Availability

Versus Frequency and Side Length



Lockheed Martin Proprietary

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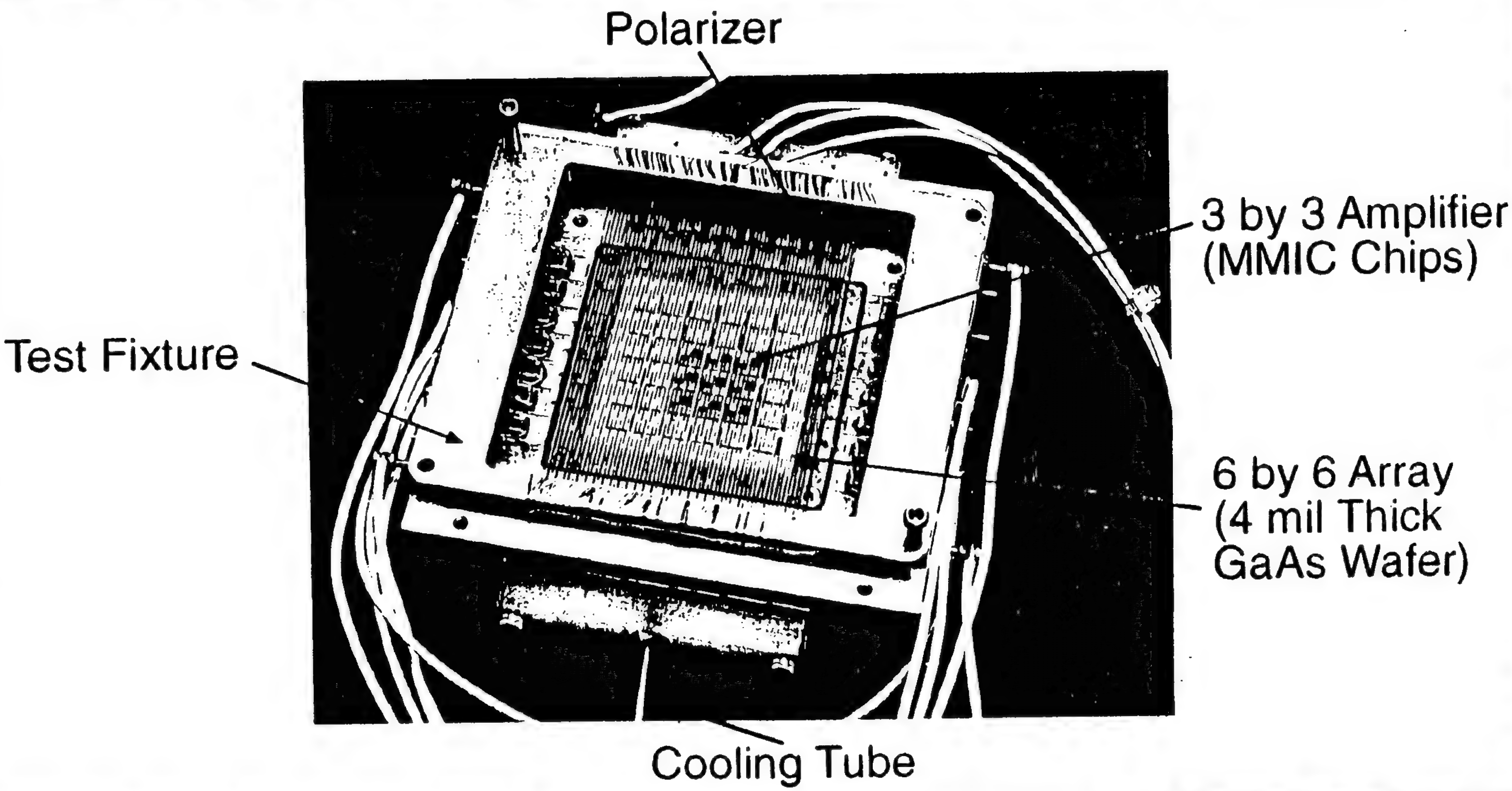
6 by 6 Array with 3 by 3 Amplifier and Polarizer in Test Fixture

MAFET

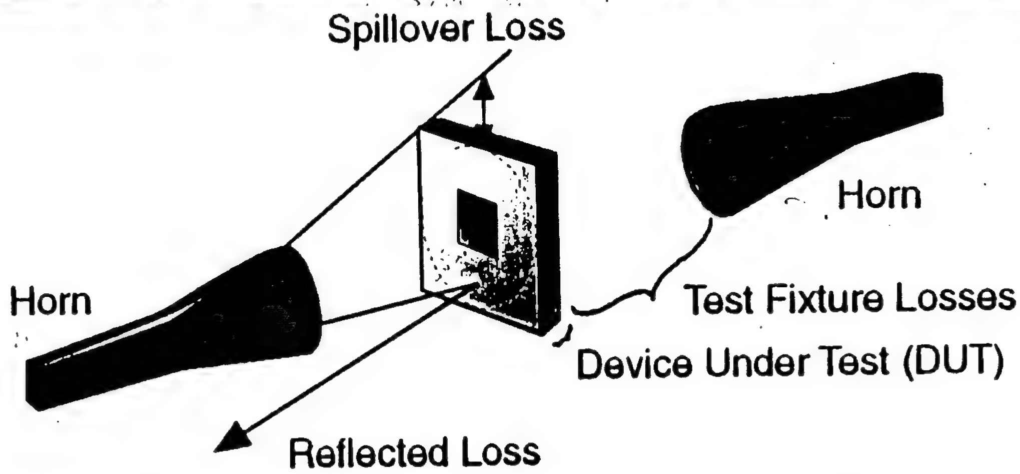


COMPETITION SENSITIVE

MARTIN MARIETTA

AR114-0098-029

Measured Results



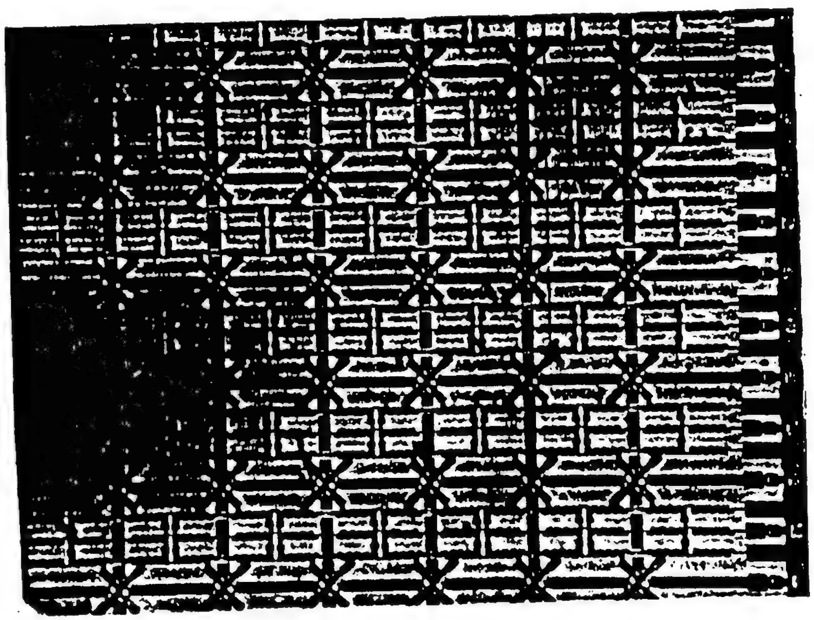
Amplifier Array (Spillover and Reflected Losses Removed)		
	Small Signal	Large Signal
Gain	14 dB	7 dB
Power output		2.5 watts

Amplifier Array with Test Fixture Losses		
	Small Signal	Large Signal
Gain	6 dB	2 dB
Power output		1 watt

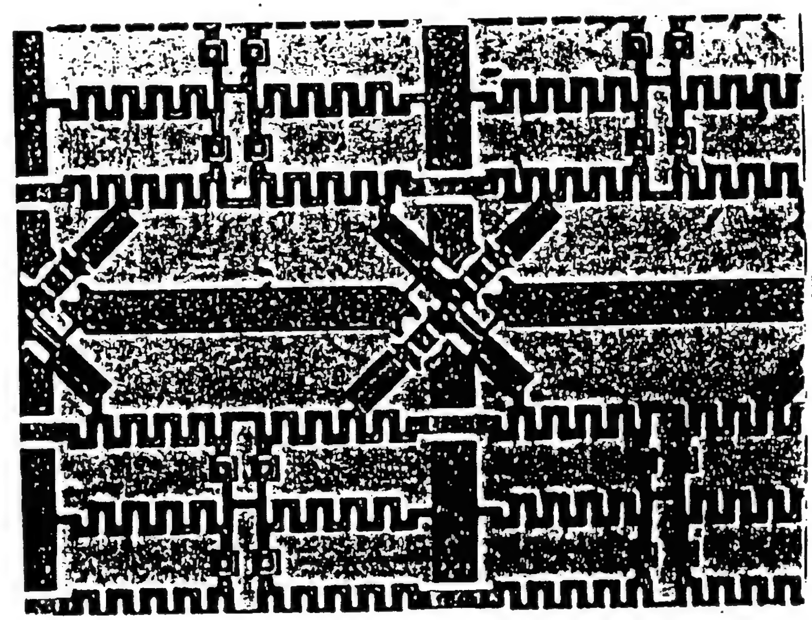
V-Band Monolithic PHEMT Grid Amplifier

(Lockheed Martin and Cal Tech)

- 36 elements at 50 GHz center frequency
- 5 dB net gain measured (May, 1995)
- 27 dB on/off ratio



36 Element
Grid Array



Single Cell
Design

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Key Elements of Amplifier Tested

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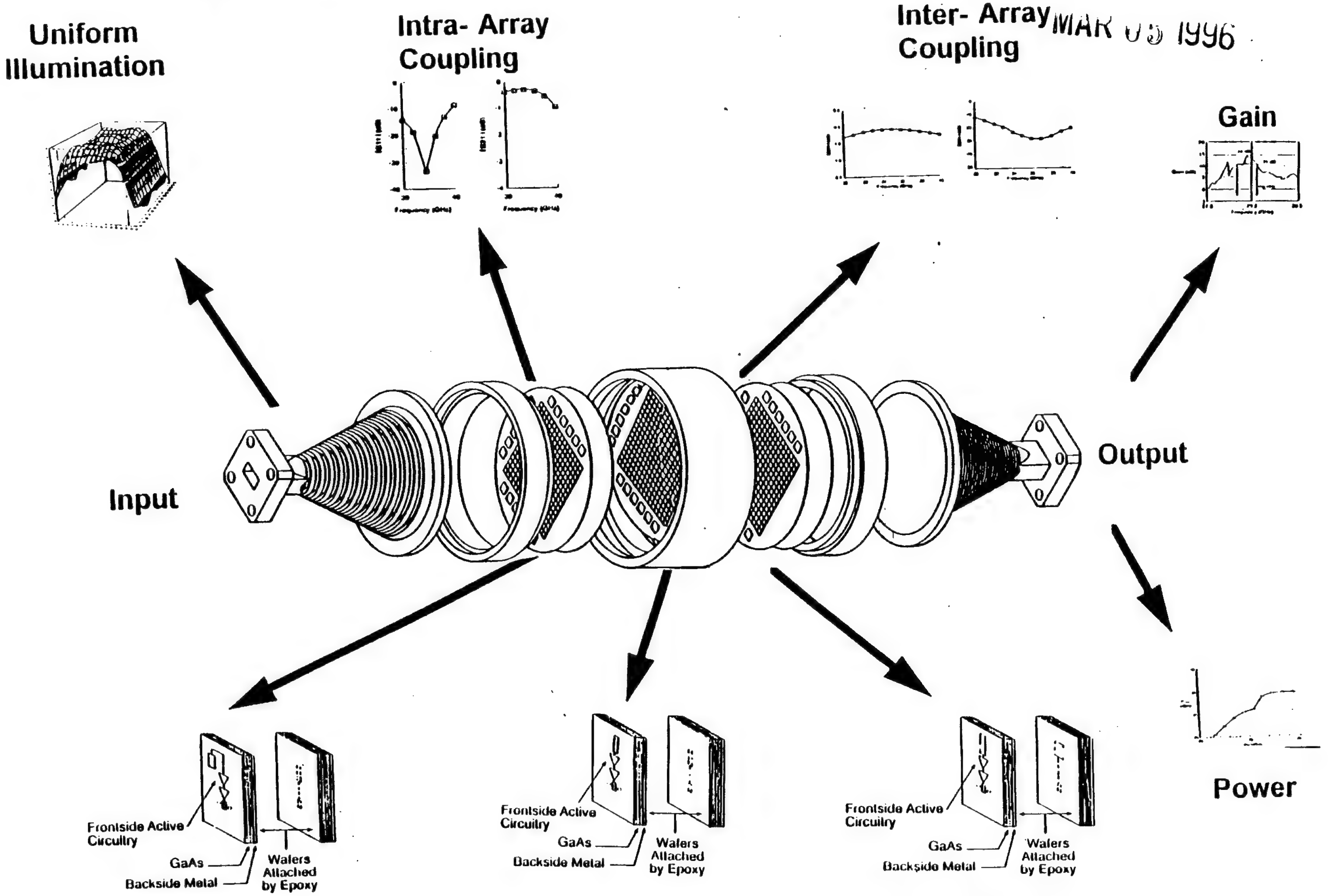

Lockheed Martin Proprietary

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Constrained Package Amplifier Results

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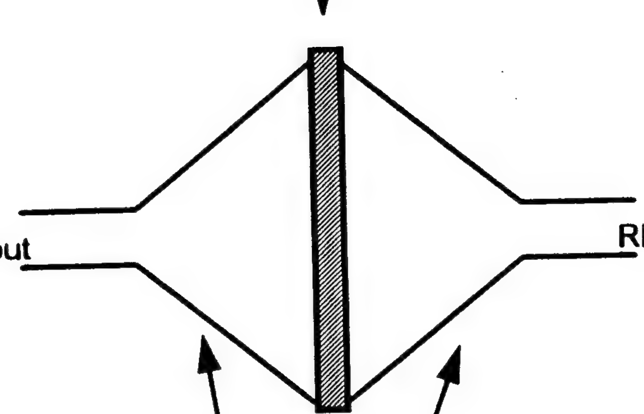

	Parameter	Value
	Frequency	X-band
	Array Size	9 elements
Hard Horn Feed	Power out	90 mw
	Total Gain	14.2 dB
	PAE	10.5%*
	Drive Power	+ 5 dBm
	Horn Pair Loss	2.2 dB
Regular Horn Feed	Power out	30 mw
	Total Gain	14.7 dB
	PAE	5.4%
	Drive Power	0 dBm
	Horn Pair Loss	1.4 dB

Results courtesy of Dr. A. Mortazawi, Univ. Central Florida

* Efficiencies as high as 16.5% and power over 100 mw measured under different conditions; second stage efficiency was 25%

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Key Results

Key Element	Yr	Development	Results
Monolithic Grid Arrays	95	Separate PHEMT and HBT amplifier arrays tested by Cal Tech (50 Ghz & 40 GHz)	**4dB/3dB gains** measured in far field
Amplifier Cells	94	2 stage cascaded MESFET cells tested in 9 element hybrid array	**12- 17 dB gain** (small signal) at 35 GHz
RF Power	95	Saturated RF Power Measurements at Ka Band with 6 element array	**2.5 watts** density measured far field
Quasi-optics Feed	95	Hard Horn concept tested at X Band and modeled at Ka Band	**1 dB uniformity** over array; 4.6 dB improved output over gaussian
Constrained Package	95	9 element X Band array tested in closed hard horn package	Far field/constrained package gains match; **PAE in high teens**
Close Coupling	94	Intra- and inter- grid coupling concepts tested with just "mils" of coupling thickness	**Low loss** (<.5 dB); wide band (>20%); low VSWR (>20 db isolation)
Liquid Cooling	94	Liquid cooling test at MMC	Demo 50 watt capacity
Cooling	95	Coupling through ground planes	Metal grd planes permit **conduction cooling**

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QUASI-OPTICS POWER AMPLIFIER CHARACTERISTICS
CURRENT AND PROJECTED

Frequency Band (GHz)	Output Power (watts)	Net Volume (cu. in.)		Weight (oz.)		P.A. Efficiency (%)	
		Now	Future	Now	Future	Now	Future
Ka	20	5	3	16	6	15-20	25-30
Ka	100	20	10	40	16	15-20	25-30
W	5	4	2	10	4	10-15	20
W	50	15	8	50	12	10-15	20

Legend

Gain: 10-12 dB
Duty: 25%
BW: > 1 GHz

GRID AMPLIFIERS

David Rutledge, Caltech

- Hybrid 10-GHz pHEMT 3.7-W grid amplifier—
  Michael DiLisio and Scott Duncan, Lockheed-Martin
- Monolithic 40-GHz HBT 650-mW grid amplifier—
  Jeff Liu and Emilio Sovero, Rockwell Science Center
- Monolithic 44–60 GHz pHEMT grid amplifier—
  Michael DiLisio and Sandy Weinreb, Lockheed-Martin

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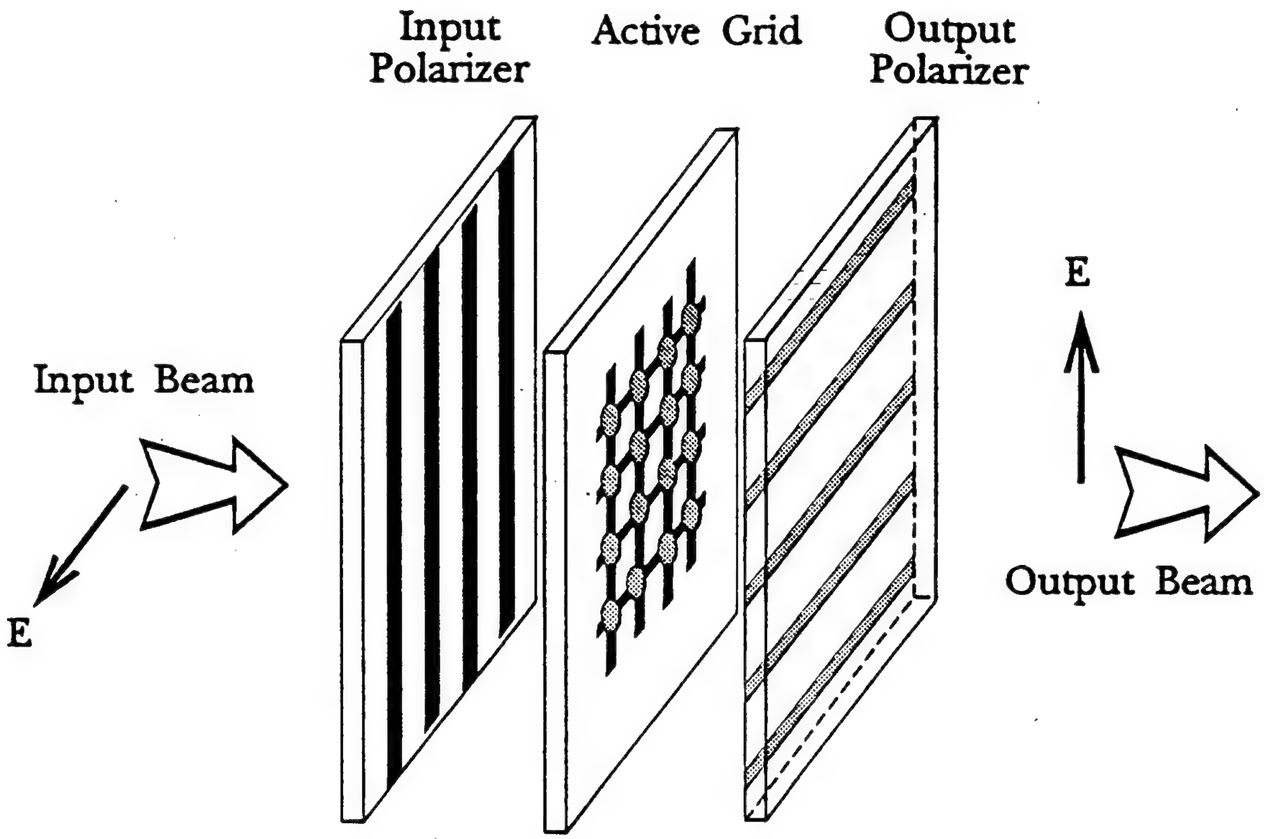
A Grid Amplifier



Cross-polarized input and output.

Provides good isolation

Allows indepenent tuning of input and output circuits through metal-strip polarizers

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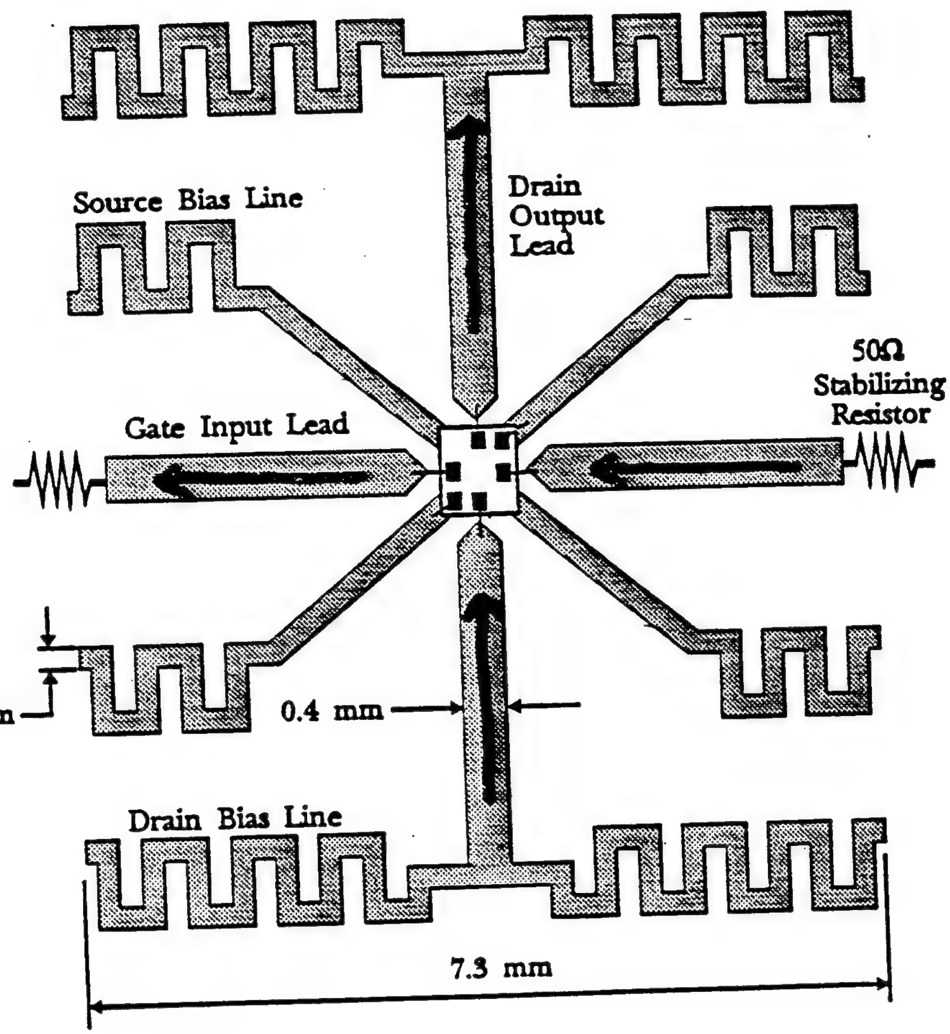
Grid Amplifier Unit Cell



10 GHz 10 x 10
0.1 μm pHEMT

Arrows indicate direction of rf current.

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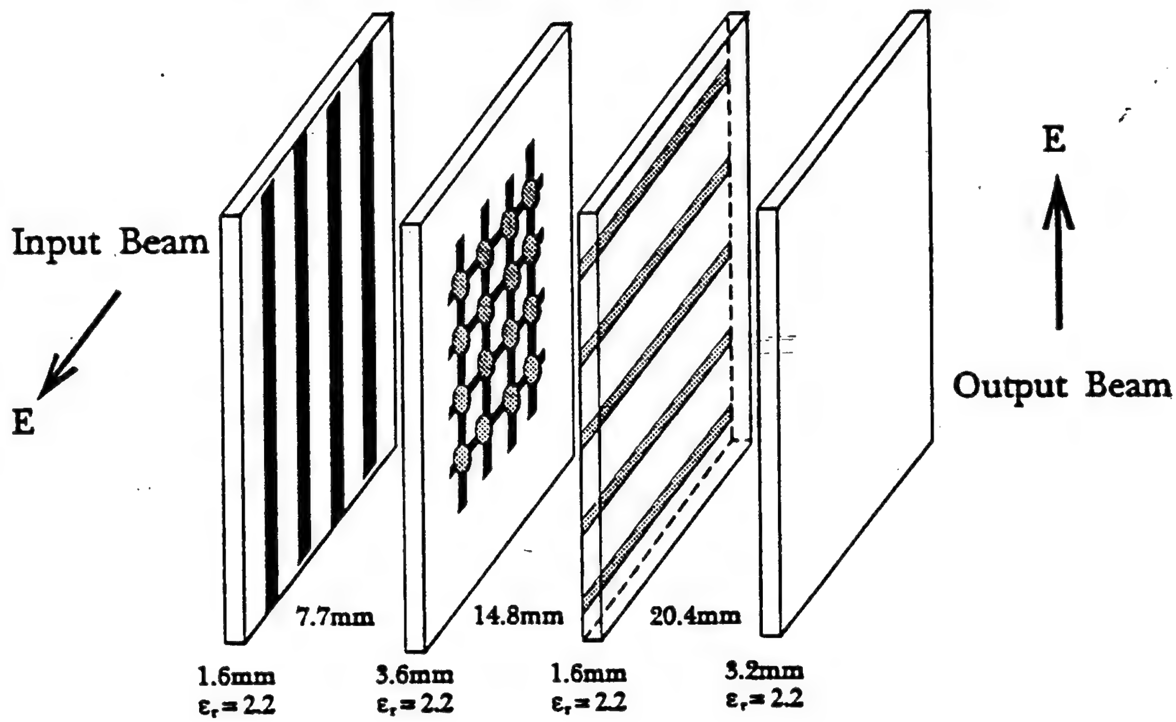
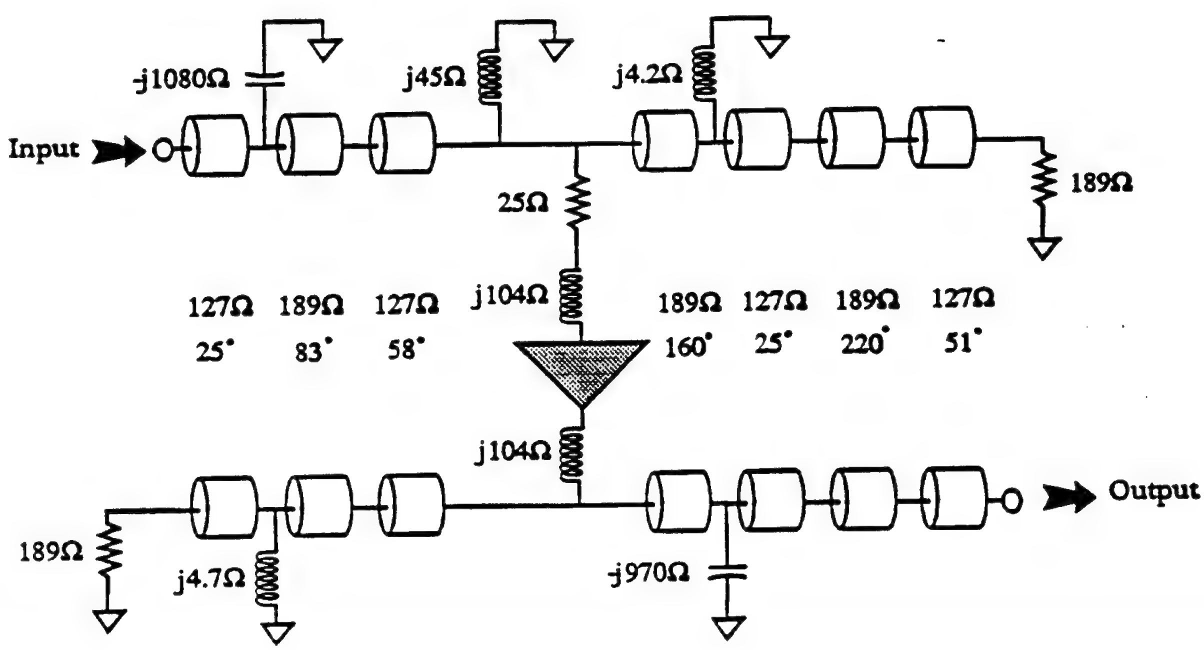
Assembled Grid Amplifier



Transmission-line Equivalent Circuit at 9GHz



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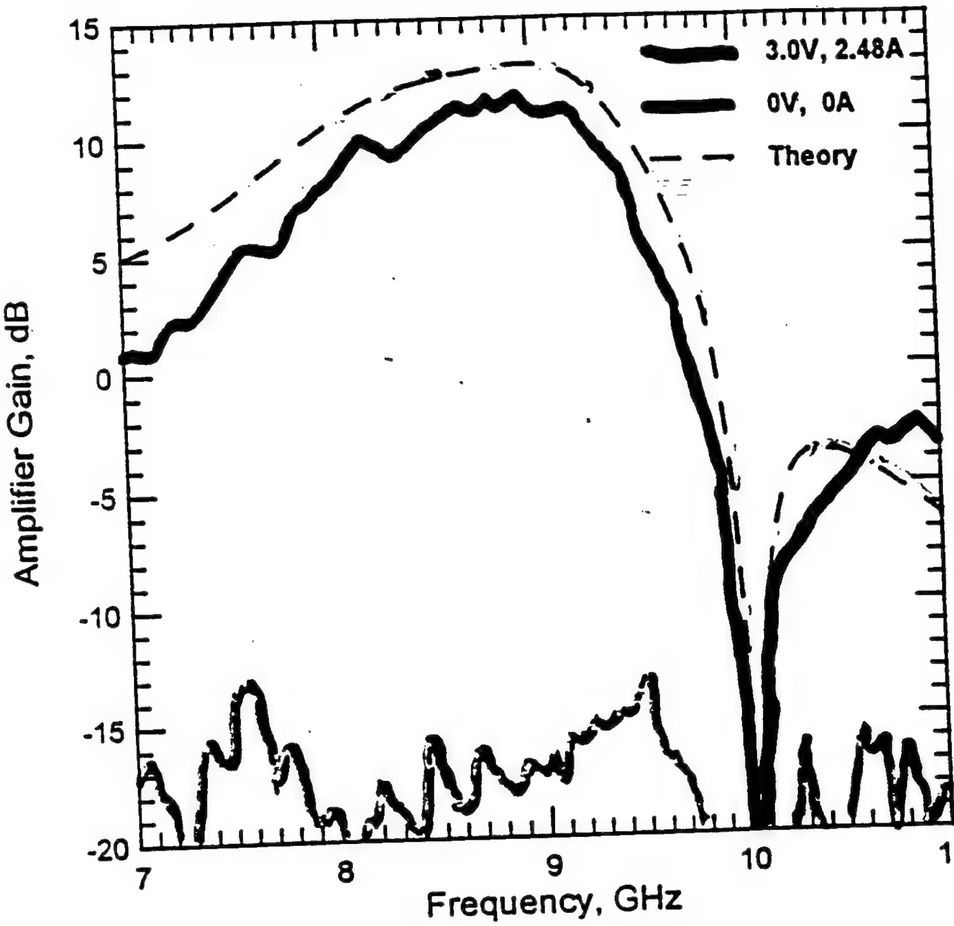
Grid Amplifier Gain Curves

Amplifier tuned to 9GHz.



Peak gain 12dB at 8.9GHz.

3-dB bandwidth of 1.3GHz (15%).

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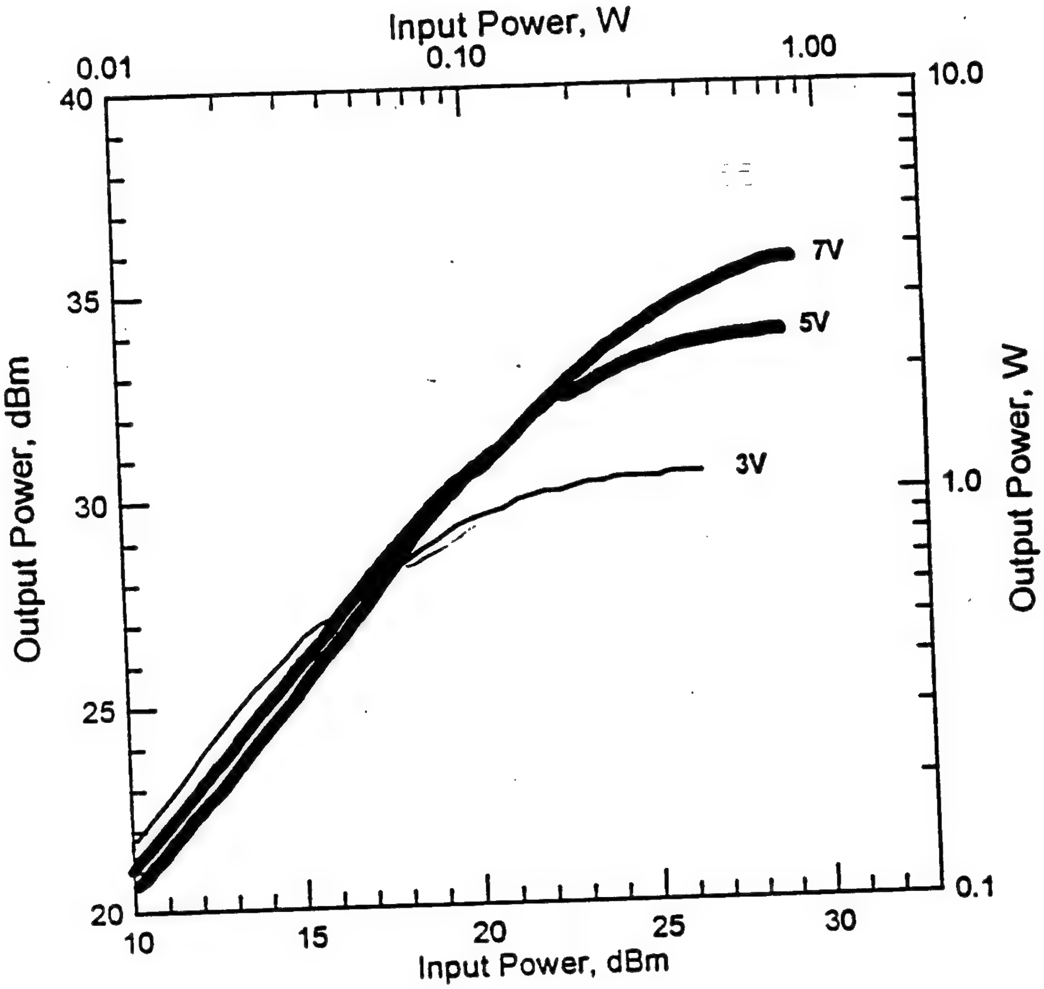
Grid Amplifier Power Saturation

Amplifier tuned to 9GHz to match TWT output



3.7W saturated output power

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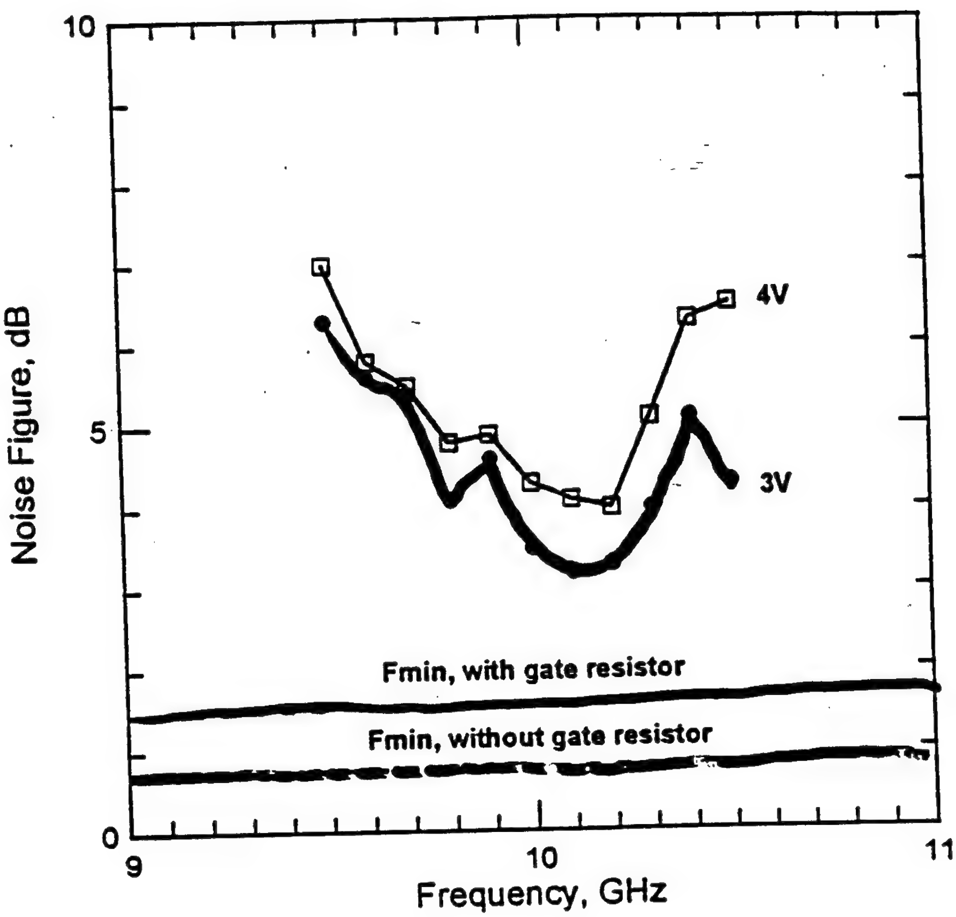
Grid Amplifier Noise Figure

10GHz amplifier with output tuner



Oscillation suppression gate resistors probably increase noise figure.

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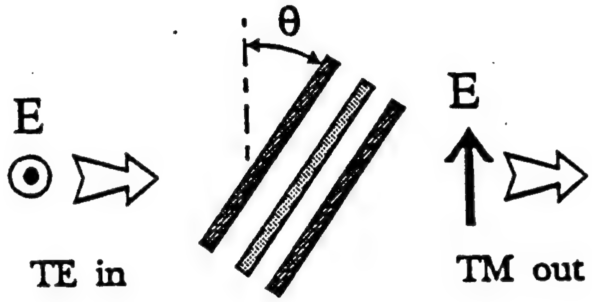
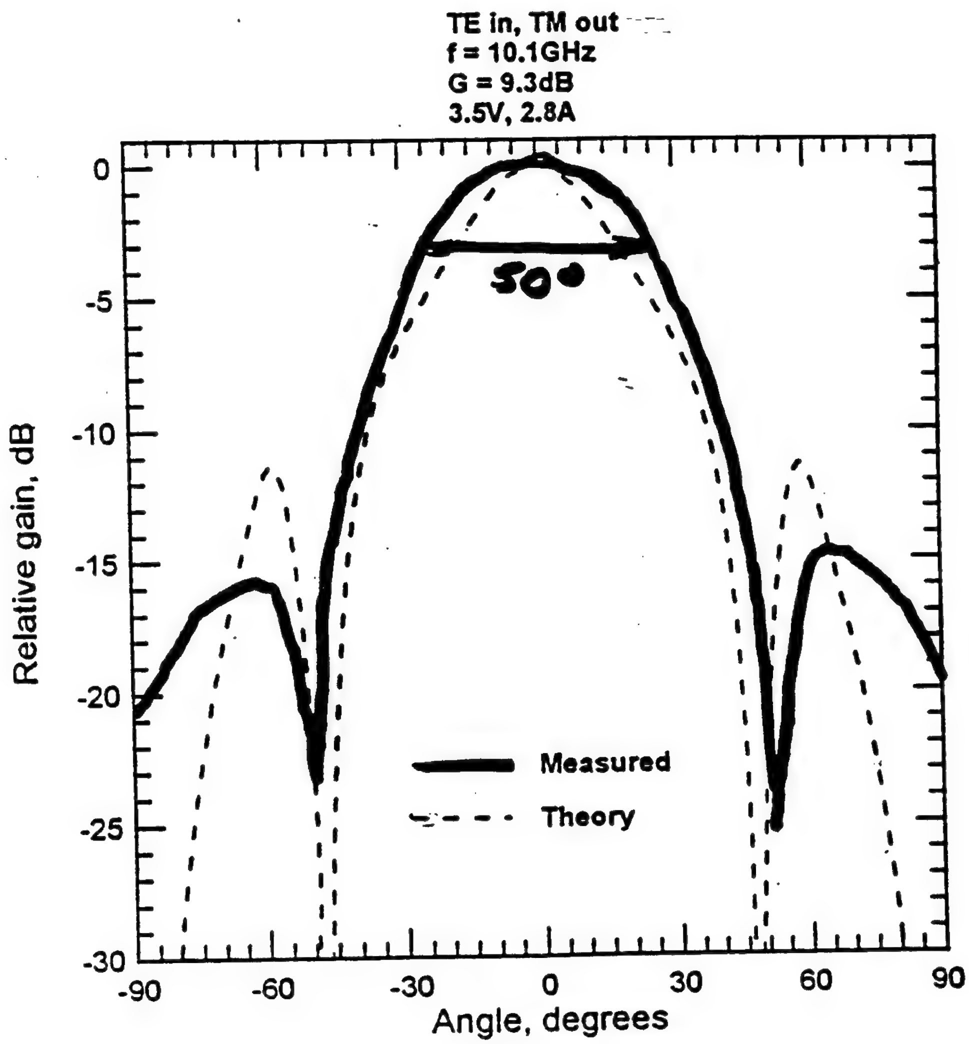
Angular Dependence



Grid Amplifier
(Output tuner removed)



Theoretical curves generated by scaling transmission line lengths by $\cos\theta_i$ and TE impedances by $\sec\theta_i$ and TM impedances by $\cos\theta_i$

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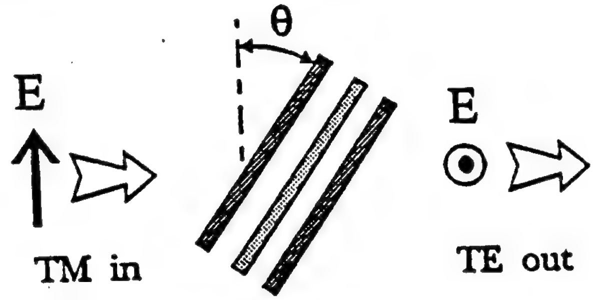
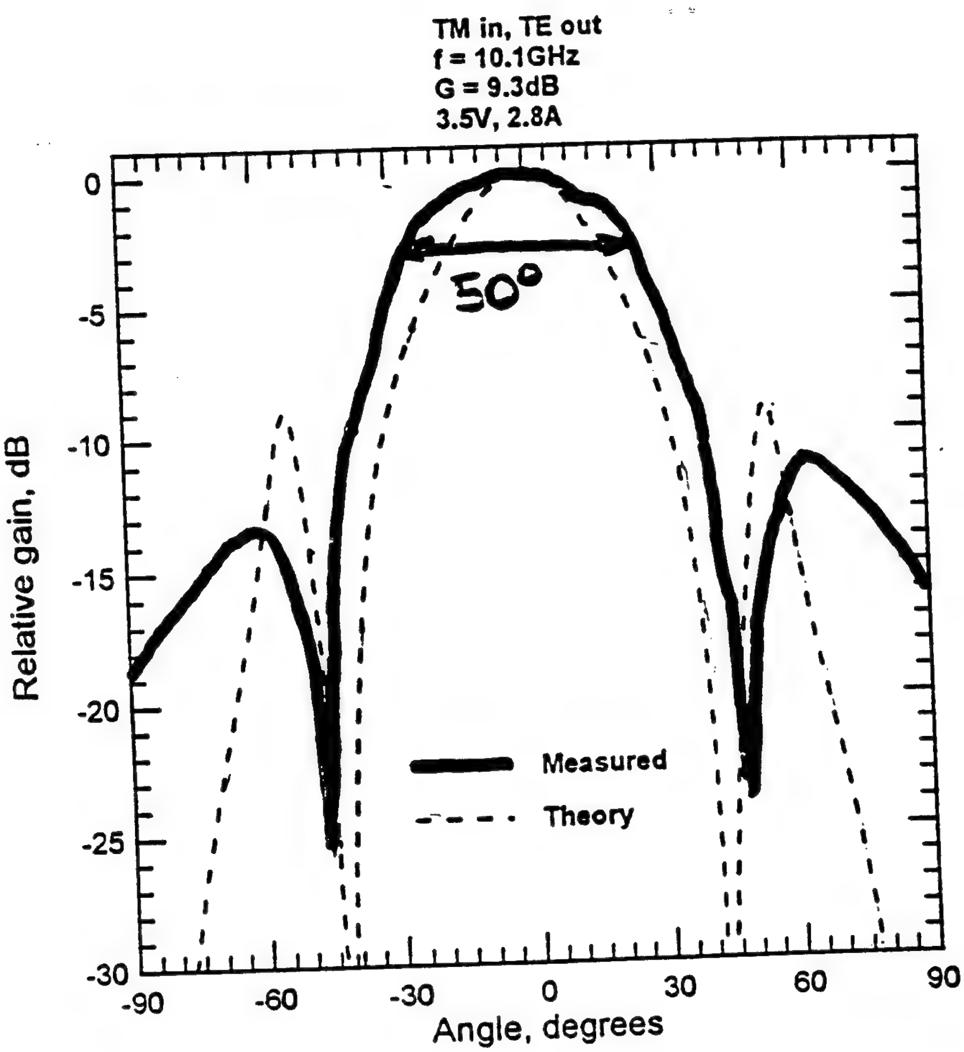
Angular Dependence



Grid Amplifier
(Output tuner removed)



Theoretical curves generated by scaling transmission line lengths by $\cos\theta_i$ and TE impedances by $\sec\theta_i$ and TM impedances by $\cos\theta_i$

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100-Element pHEMT Grid Amplifier

Chips fabricated by Lockheed Martin Laboratories, Baltimore

Summary of Results

- Gain and stability models developed and verified.
- Grid constructed using Martin Marietta 0.1-um pHEMT's.
- Spurious common-mode oscillations suppressed with chip resistors in the gate leads.
- Measured gain of 10dB at 10GHz and 12dB at 9GHz.
- 15% 3-dB bandwidth at 9GHz.
- Accepts beams with incidence angles up to 30°.
- Measured minimum noise figure of 3dB at 10GHz.
- 3.7W maximum saturated output power at 9GHz.
- Peak power-added efficiency of 12% at 9GHz.
  Peak device efficiency of 20%.

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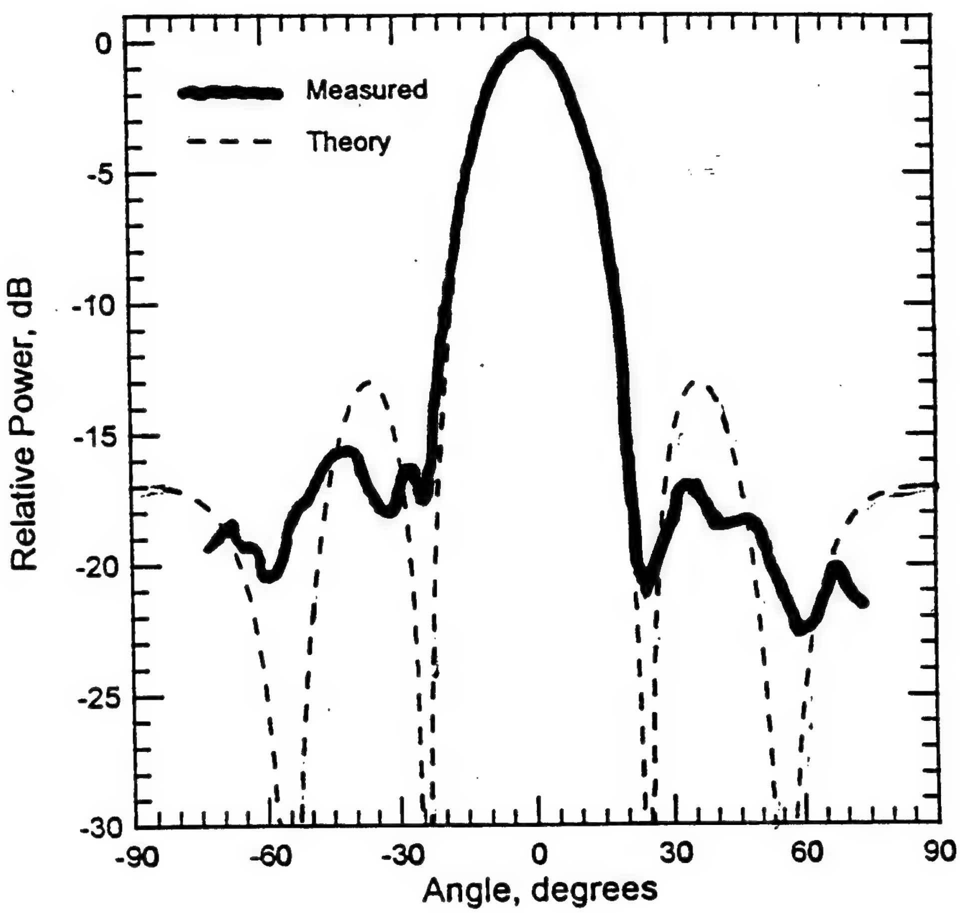
Grid Amplifier Output Radiation Pattern

H-plane pattern of grid tuned for 10GHz without output tuner.

Normally-incident input.



Theoretical pattern assumimg uniform array of 10 elemntary dipoles spaced 7.3mm apart.

Measured pattern is diffraction-limited.

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GRID AMPLIFIERS

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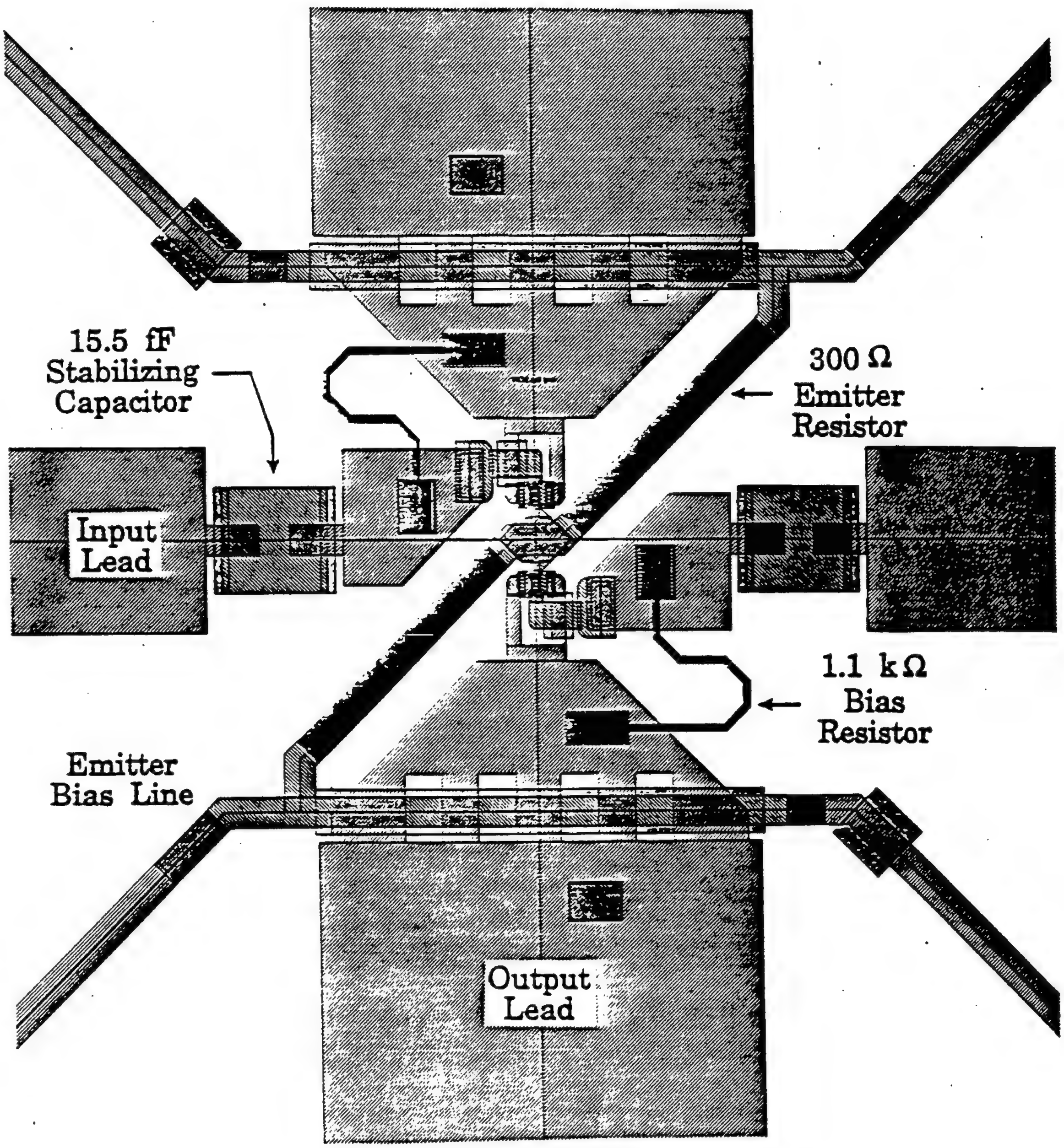
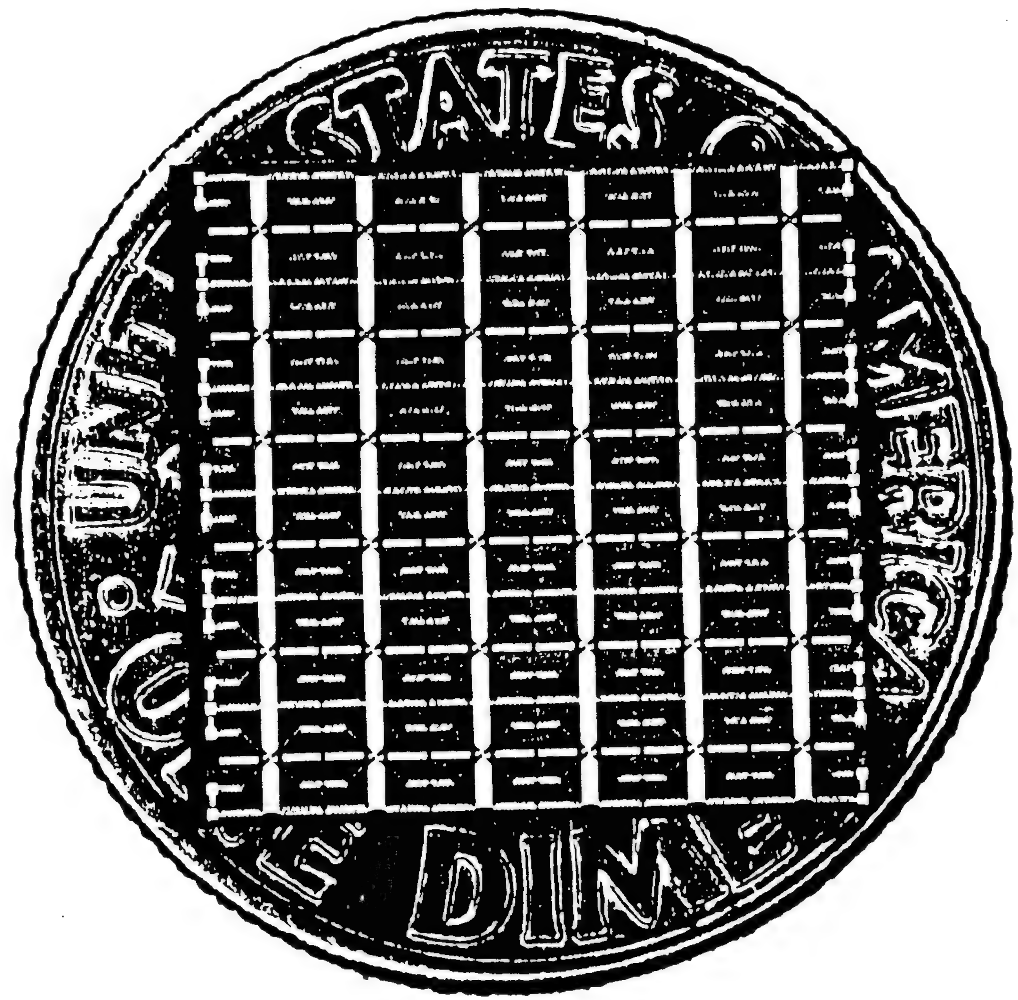
Rockwell HBT Layout

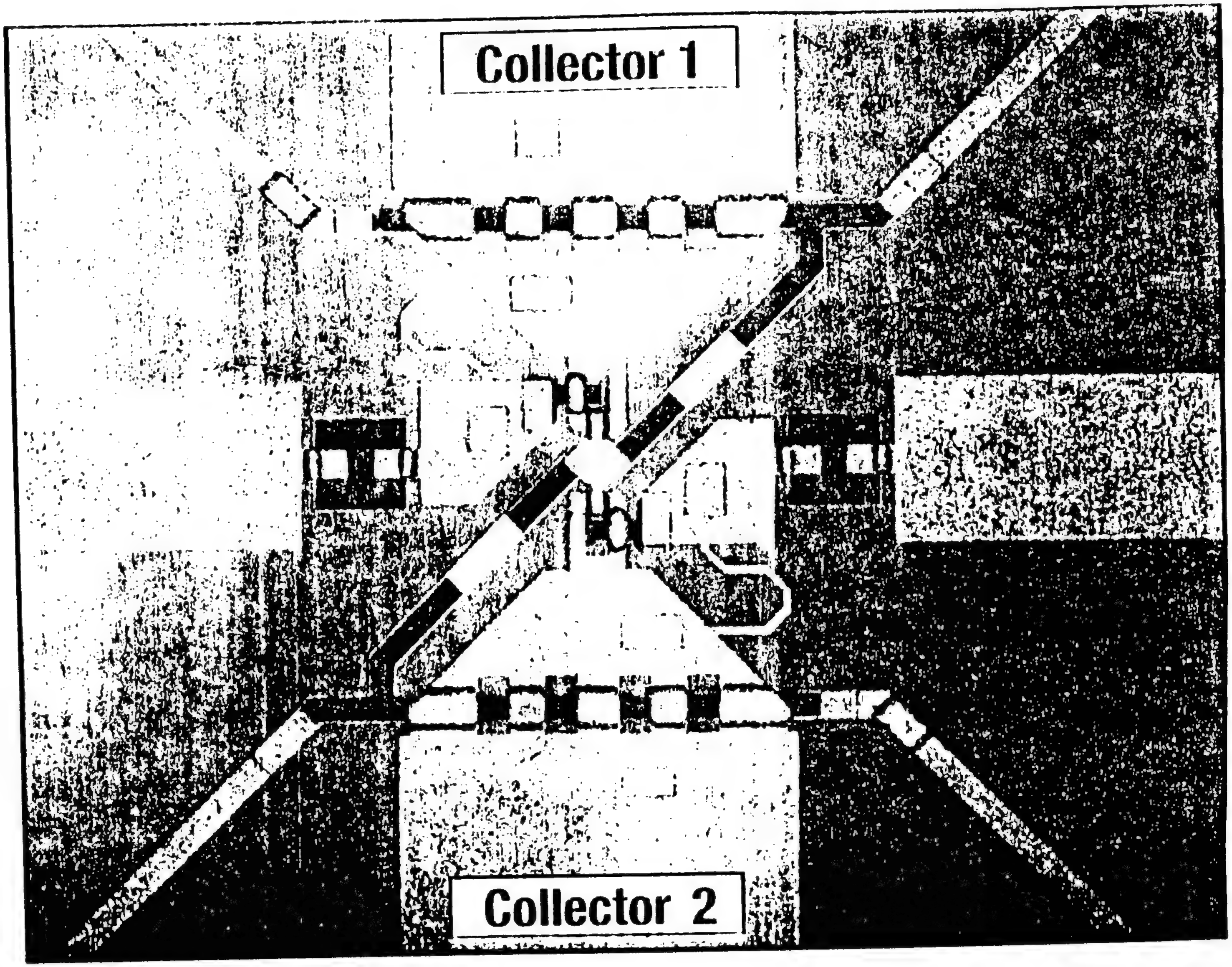


Monolithic Grid Amplifier

SCP0816A.041395



Rockwell
Science Center



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Rockwell
Science Center

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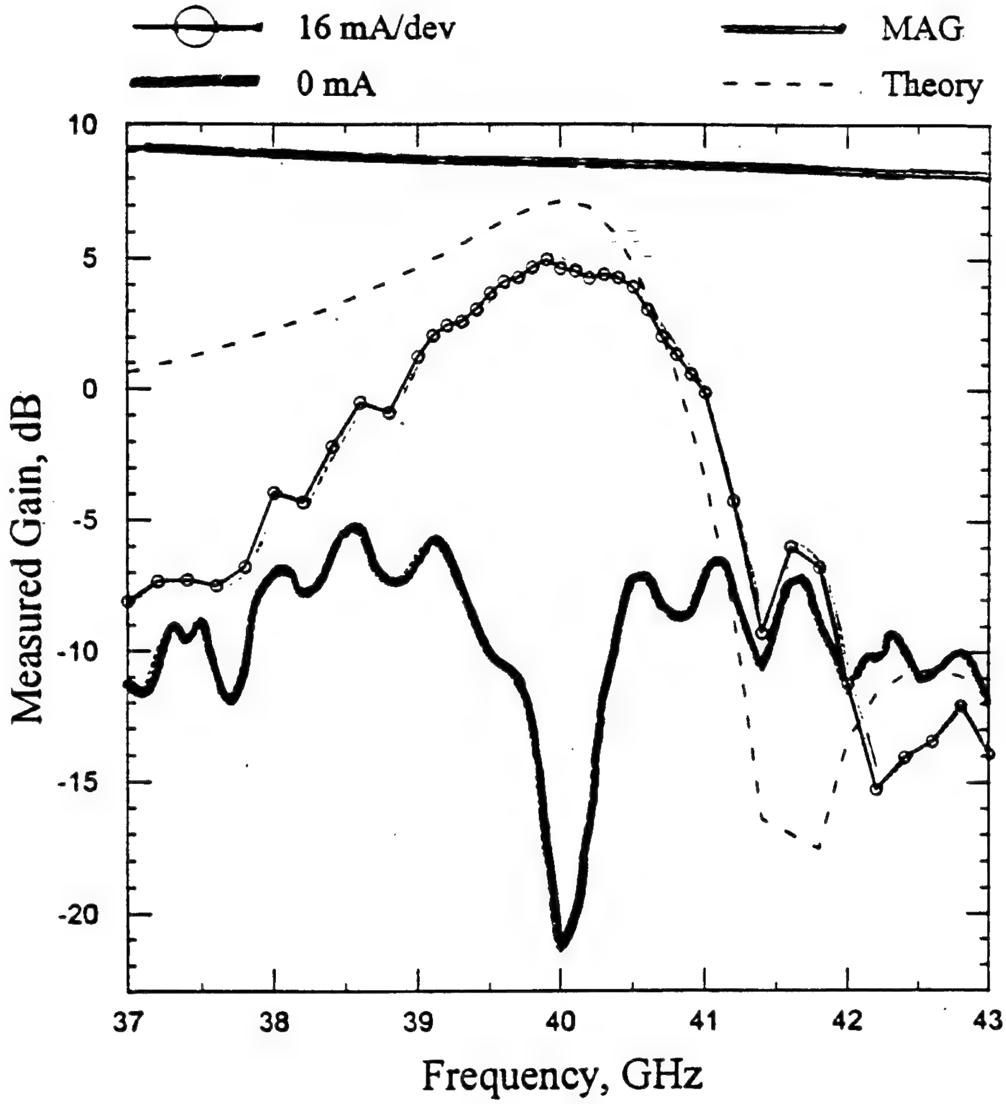
Monolithic HBT Grid Amplifier
Gain Response



Gmax: 5 (dB) @ 40 (GHz)
3-dB bandwidth: 1.8 GHz ; 4.5 %

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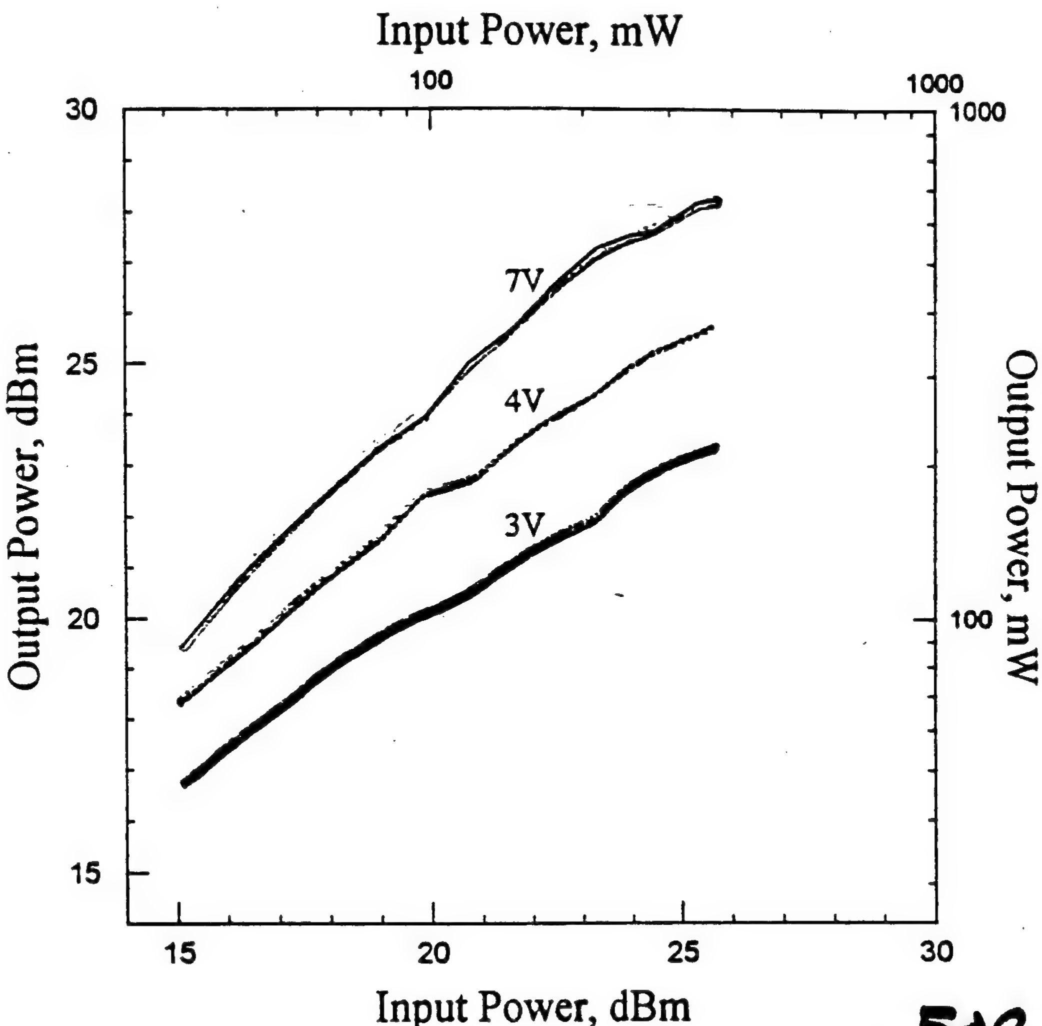
Monolithic HBT Grid Amplifier
Output Power vs. Input Power



Max. Output Power: 670 mW

5dB small signal

2.5dB gain (Limited input power)

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Summary of Monolithic HBT Grid Amplifier

Gain Measurement

G_{max}: 5dB @ *40*GHz

3-dB Bandwidth: *1.8*GHz ; *4.5%*

Power Measurement

Maximum Output Power: *670*mW

Maximum Power-Added Efficiency: *4%*

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GRID AMPLIFIERS

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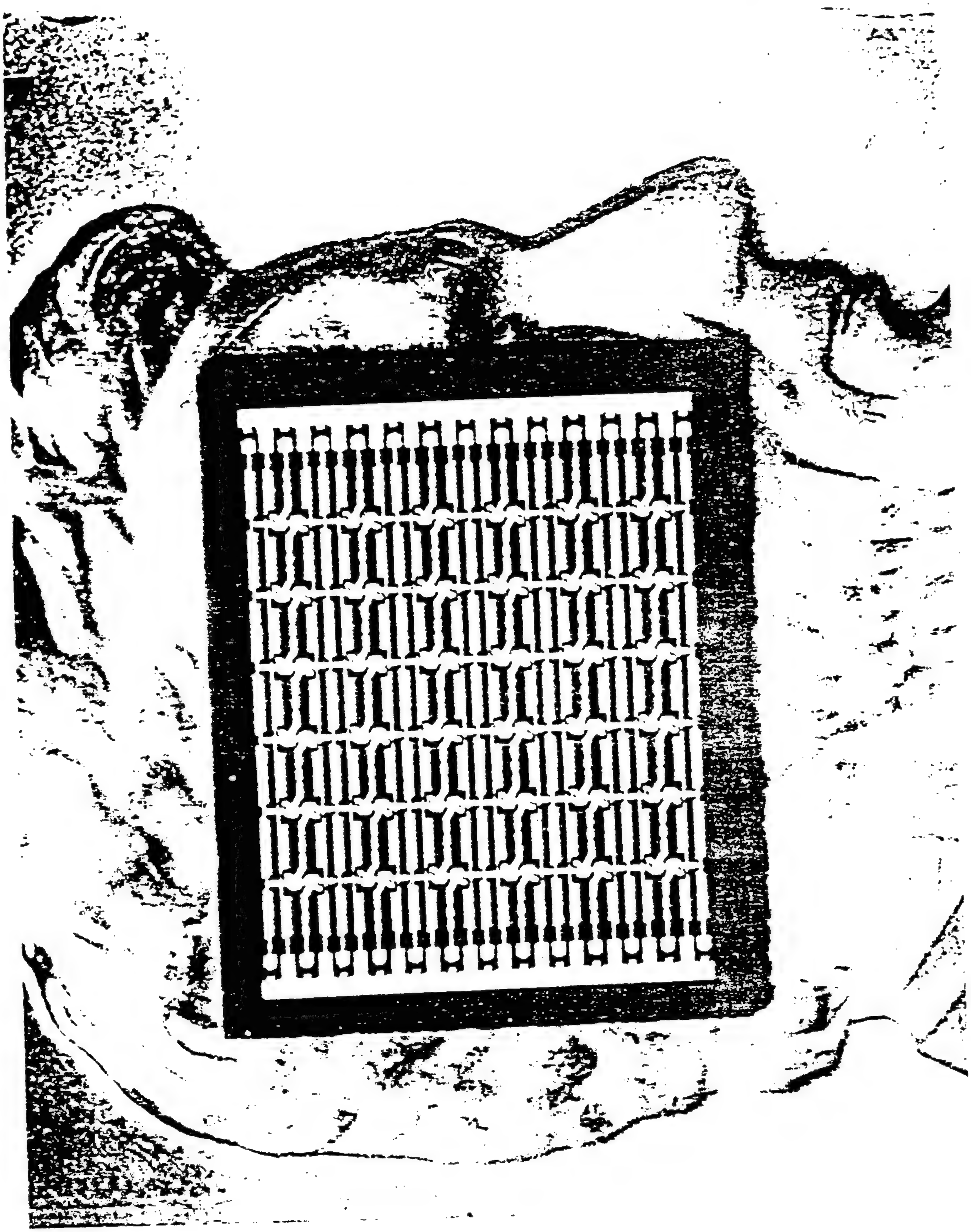

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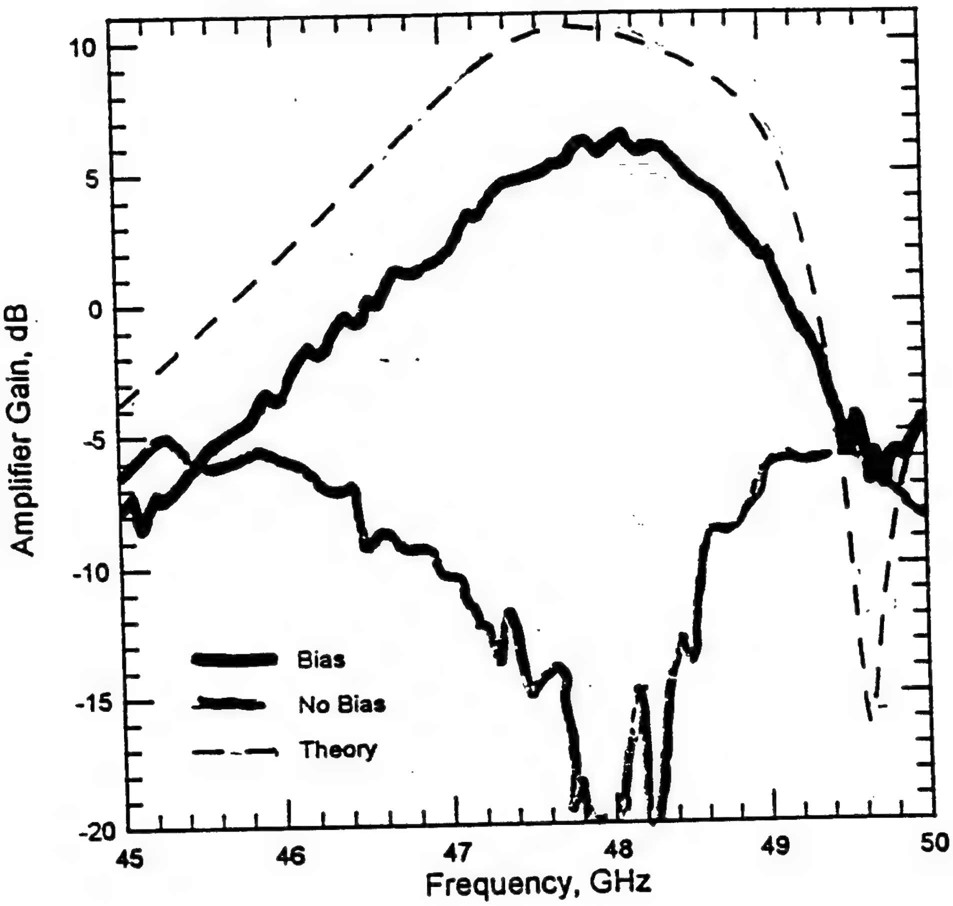
Grid Amplifier Gain Curves

Amplifier tuned to 48GHz.



Peak gain 6dB at 48GHz.

3-dB bandwidth of 1.7GHz (3.5%).

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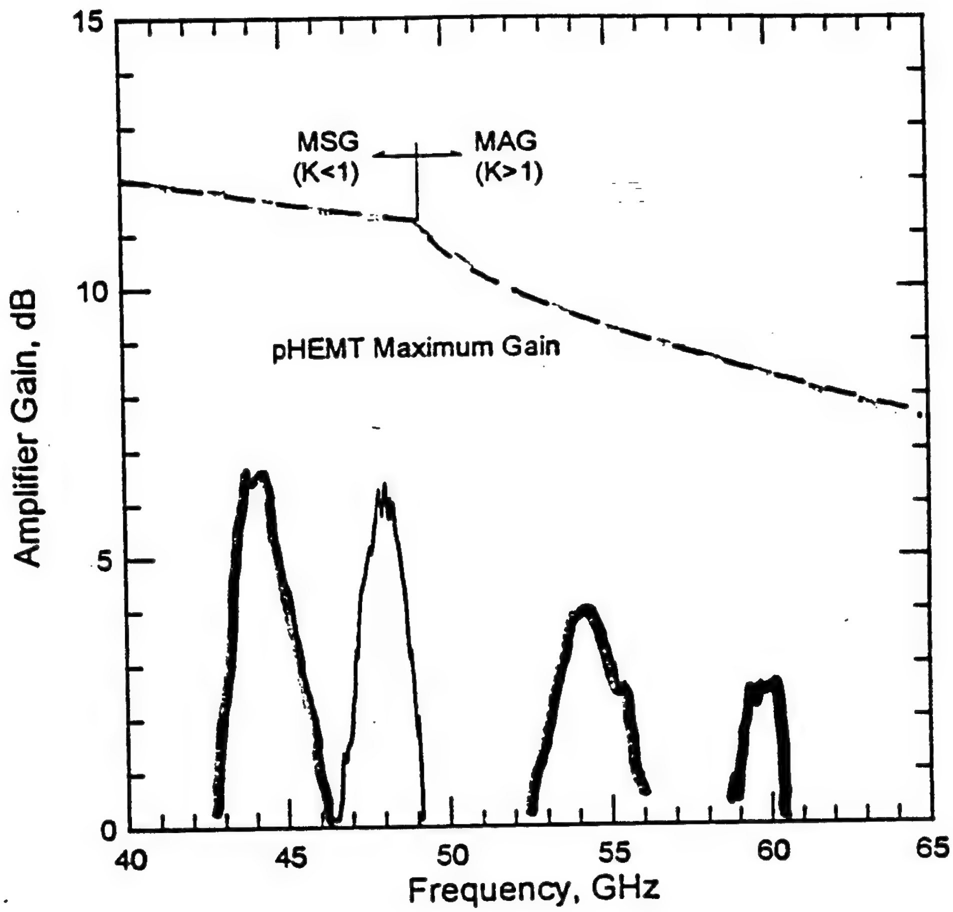
Grid Amplifier Tuning Range



44-60GHz tuning range.

Output tuner used for 60GHz gain curve.

Caltech

36-Element Monolithic pHEMT Grid Amplifier

Grids fabricated at Lockheed Martin Laboratories, Baltimore

Summary of Results

- Grid constructed with Lockheed Martin 0.1-um pHEMT's.
- Grid can be tuned by changing polarizer/tuner positions. Measured gain of 6.5dB at 44GHz and 2.5dB at 60GHz.
- 6% 3-dB bandwidth at 54GHz.
- Gain reduced by 5dB—possibly due to diffraction losses from the small grid ($\lambda/2$).
- Could be used as a Travelling Wave Tube (TWT) replacement.

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GRID AMPLIFIERS

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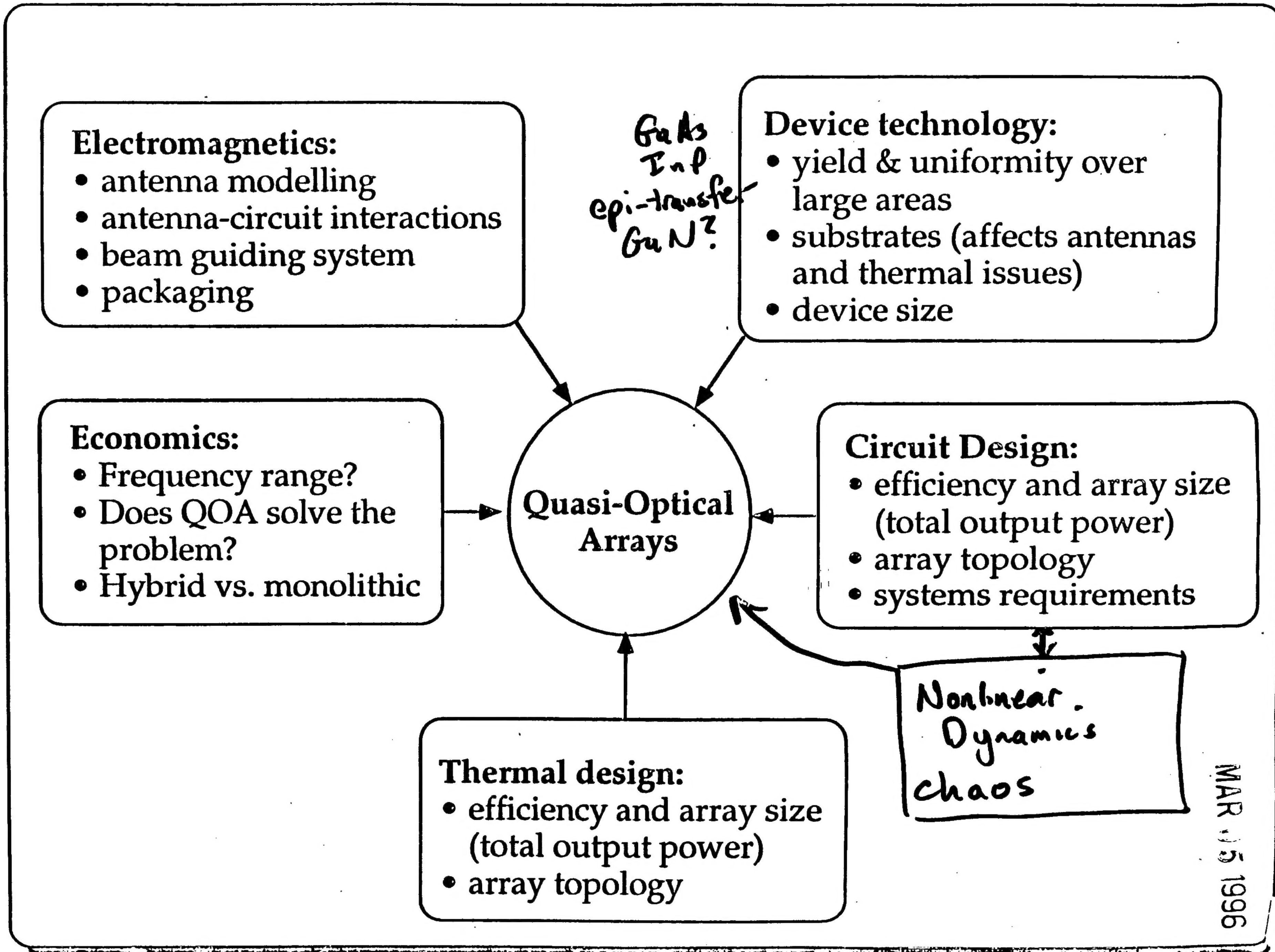
rayork@ece.ucsb.edu

UC SANTA BARBARA

- coupled oscillator systems & modelling
- Novel scanning concepts
- integrated antenna design
- antennas for arrays
- modelling of arrays & grids using FDTD
- amplifier arrays
- Quasi-optical distributed circuits

conventional antennas vs. grids

supported by ARO, NSF, Rockwell Science Center, Hughes Research Laboratories, Jet Propulsion Lab


Electromagnetics:
• antenna modelling
• antenna-circuit interactions
• beam guiding system
• packaging
GaAs
InP
epi-transfer
GaN?
Device technology:
• yield & uniformity over large areas
• substrates (affects antennas and thermal issues)
• device size
Economics:
• Frequency range?
• Does QOA solve the problem?
• Hybrid vs. monolithic
Quasi-Optical Arrays
Circuit Design:
• efficiency and array size (total output power)
• array topology
• systems requirements
Nonlinear Dynamics
chaos
Thermal design:
• efficiency and array size (total output power)
• array topology